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Primary voltage and current control for an autonomous inverter-based microgrid

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Abstract

This paper presents a new technique to design the voltage and current controllers in an inverter-based microgrid. The proposed method provides a systematic approach to design the controllers based on Lyapunov theory, and does not utilize the conventionally employed Proportional-Integral (PI) controllers, which are difficult to tune. Also, the use of PI controllers requires the simultaneous synchronization of tuning parameters in different stages of a larger system that render their use to be extremely tedious for large industrial applications. The novelty of the proposed controllers lies in the methodical design procedure and a flexibility to model the controller without analyzing the system equations and eigenvalues. Lyapunov Direct Method has been used to design the controllers for adequate active and reactive power sharing among different Distributed Energy Resources (DERs) present in a microgrid. The proposed controller has been tested on a test system and has manifested its advantage over its conventional counterpart in terms of less settling time, lower overshoot, and zero steady-state error in the observed control signals, along with expected objectives of adequate power sharing and voltage regulation in the system.

Keywords: Microgrid, Lyapunov Theory, inverter, voltage control, current control.

1. Introduction

With a momentous increase in the integration of Distributed Energy Resources (DERs) to the conventional power grid, the concept of microgrid has gained widespread popularity in the research and development arena. Microgrids are controllable entities incorporating generation, loads, and associated control structure. These entities have the ability to function either independently (islanded mode) or in grid-connected mode and have proven to be a viable solution to maintain load point supply security and minimization of outage intervals in case of faults on the main distribution system [1]. The incorporation of DERs in the power system increases the possibility of local voltage regulation, power factor correction, mitigation of power quality issues, etc., which cannot be achieved in the prevalent centralized generation [2]. Most of the conventional generators are 50/60 Hz machines, whereas droop-based DERs work on different operating frequencies, depending upon their type, and are interfaced with the power grid via inverters. For the operation of DERs in grid-connected mode, the system dynamics are enforced by the grid, due to the relatively small size of DERs [3], [4]. On the other hand, during the independent operation of a microgrid, each inverter generates its own dynamics which are dictated not only by the DER characteristics but also by the associated network [5]. The control of each inverter-based microgrid is, therefore, an important consideration for the smooth and successful operation of a microgrid in both operating modes.

The basic control objective in an inverter-based microgrid is the meticulous power sharing among inverters while simultaneously maintaining their frequency and voltage profiles in acceptable limits [6]. Three control levels are used to ensure a successful operation of the microgrid in islanded mode. The first control stage is termed as the primary control that maintains the voltage magnitudes and frequency in the microgrid. This control layer, however, is prone to deviations in both the control parameters, that are then catered for in the second control stage, secondary control [7], [8]. The third layer of the microgrid control structure, tertiary control, is only responsible for the flow of power among microgrids in islanded mode

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[9]. Primary control schemes[a] are employed at the local level, whereby each inverter is associated with its own control structure. This control structure is responsible for maintaining the voltage magnitudes and frequency of each inverter in an islanded microgrid. The secondary control mechanism is employed as a second layer of the microgrid control structure. Two broad categories of this control scheme are available in the literature, namely: centralized and decentralized control. Centralized secondary control architecture uses communication infrastructure or signal injection techniques to accurately share power among various inverters. These techniques add complexity to the network and also increase the overall cost of the system. Conversely, decentralized control structures allow more flexibility of operation in the microgrid systems [10].

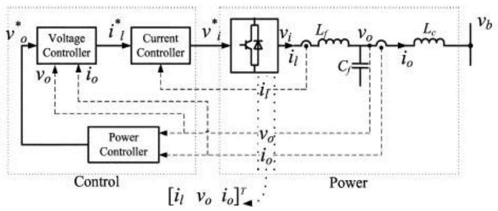

Fig. 1. Control Structure of Inverter-Based DER [5].

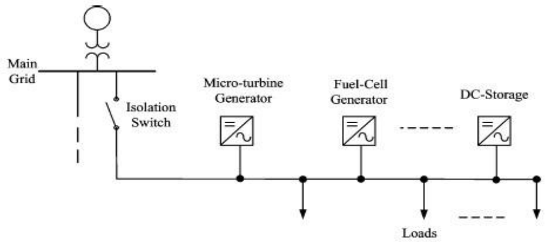

Fig. 2. Typical Inverter-Based Microgrid Structure.

Various secondary control approaches are presented in literature including droop controllers [11], feedback linearization [12], static droop compensator [13], and harmonic based droop controller [14]. However, primary control mechanisms, alternative to droop control, have not been widely discussed. Basic voltage and current control strategies, employing conventional PI controllers are presented in [5] and have been used without any modifications in most of the papers for the design of secondary and tertiary control algorithms. Fundamental droop control approach, that mimics the governor operation of a conventional synchronous generator, is used to model the power controller, which sets the reference value for voltage controller. The output of this voltage controller serves as the reference value of the current controller. The cascade of these three controllers models the entire primary control scheme for inverter-based DER.

This paper proposes a novel primary control structure based on Lyapunov theory. The proposed controller eliminates the need for manual tuning of controller gains and also presents a systematic approach towards the controller design.

The remainder of this paper is organized as follows. Section 1.1 presents the modelling of inverters and Section 1.2 provides a basic understanding of Lyapunov theory. Control design procedure for current and voltage controllers is detailed in Section 2 and the results of simulations, based on a test system, are presented in Section 3. Section 4 concludes the paper.

1.1. Modelling of an inverter-based microgrid

A typical inverter-based microgrid structure is shown in Fig.1. This structure consists of different types of DERs that are connected to the power grid via inverters. These DERs may be of various types including photovoltaic sources, fuel cells, DC storage units, microturbines, etc. The isolation switch is used to determine the mode of operation of these microgrids, whereby they can either operate in autonomous or in the grid-connected mode. In the context of this paper, we focus primarily on the autonomous mode of microgrid operation and control. The associated control structure of these inverter-based DERs is depicted in Fig. 2, where three different controllers are employed for the primary control architecture. A three-legged Voltage Source Inverter (VSI) along with an LC filter and a coupling inductor forms the source power circuit of the microgrid [15]. The LC filter and the coupling inductor can also be viewed as an LCL filter. The modelling approach of inverters utilizes the fact that in islanded operation, each inverter will synthesize its own operating frequency and hence there is a need to transfer the parameters of all inverters on a single reference frame. A random inverter rotating reference frame is chosen as the microgrid reference and the parameters of all other inverters are transferred to this reference. The frequency of rotation of this reference frame is termed as ω_n.

The mathematical model of the power controller is obtained using the droop theory. Since the power controller sets the frequency and magnitude of the voltage, it is modelled on the principles of droop employed in conventional synchronous generators. The droop mimics the governor behaviour in a synchronous generator and alters its frequency depending upon the variation in load, i.e. the active power. The same droop principle is also used for the voltage magnitude and reactive power relationship. The active power sharing among inverters is achieved based on the following equation:

$$\omega = \omega_n - m_p P \tag{1}$$

where ω is the frequency of the inverter, m_p is the droop gain of $P - \omega$, ω_n is the nominal frequency, and P is the active power of the inverter. It can be observed from (1) that ω is dependent on m_p , and the angle α of the inverter reference frame observed from the microgrid reference frame is given by:

$$\alpha = -\int m_p P \, dt \tag{2}$$

This expression is obtained by integrating the inverter frequency over time. It is evident that α varies in response to the real power, with a gain dependent upon the value of the droop coefficient. To share the reactive power Q among various inverters, a droop is introduced in the voltage magnitude as shown below;

$$v_{od_{ref}} = V_n - n_q Q \tag{3}$$

where V_n is the nominal voltage, n_q is the droop gain of $Q - V$, and $v_{od_{ref}}$ is the d-axis reference value of output voltage. On a similar note as for the active power sharing, the reference d-axis voltage is dependent upon the nominal voltage of the inverter and the droop coefficient. Since all parameters are modelled in Park's dq reference frame, it is worth noting that the reference of the voltage is set only according to the d-axis voltage component while the q-axis component is set as zero. The two droop coefficients used in (1) and (3) can be computed according to the following two expressions [5]:

$$m_p = \frac{\omega_{max} - \omega_{\min}}{P_{max}} \tag{4}$$

$$n_q = \frac{V_{od_{max}} - V_{od_{\min}}}{Q_{max}} \tag{5}$$

where $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum values of frequency, respectively. $P_{\max}$ and $Q_{\max}$ are the maximum active and reactive power values, respectively. The decoupling of active and reactive power can be achieved by shaping the output impedance of the inverter. This is done using the coupling inductor. The mathematical model of the LCL filter is given by the following equations [5]:

$$\frac{di_{ld}}{dt} = -\frac{r_f}{L_f} i_{ld} + \omega i_{lq} + \frac{1}{L_f} v_{id} - \frac{1}{L_f} v_{od} \tag{6}$$

$$\frac{di_{lq}}{dt} = -\frac{r_f}{L_f} i_{lq} - \omega i_{ld} + \frac{1}{L_f} v_{iq} - \frac{1}{L_f} v_{oq} \tag{7}$$

$$\frac{dv_{od}}{dt} = \omega v_{oq} + \frac{1}{C_f} i_{ld} - \frac{1}{C_f} i_{od} \tag{8}$$

$$\frac{dv_{oq}}{dt} = -\omega v_{od} + \frac{1}{C_f} i_{lq} - \frac{1}{C_f} i_{oq} \tag{9}$$

$$\frac{di_{od}}{dt} = -\frac{r_c}{L_c} i_{od} + \omega i_{oq} + \frac{1}{L_c} v_{od} - \frac{1}{L_c} v_{bd} \tag{10}$$

$$\frac{di_{oq}}{dt} = -\frac{r_c}{L_c} i_{oq} - \omega i_{od} + \frac{1}{L_c} v_{oq} - \frac{1}{L_c} v_{bq} \tag{11}$$

where i_l is the filter inductor current, L_f is the filter inductance, and r_f is the associated resistance of the filter. v_o and i_o are the output voltage and current, respectively. L_c is the coupling inductance, and C_f is the capacitance of the filter. The aim of the voltage and current controllers is to provide sufficient damping to the above-modelled LCL filter.

1.2. Lyapunov theory

Lyapunov theory is one of the most generic approaches to determine the stability of dynamic systems. Unlike other stability methods, it does not rely upon the solution of system equations or eigenvalue analysis but provides a system energy-based approach to stability analysis. Lyapunov theory proposes two methods for the stability analysis of linear and nonlinear systems, namely, the linearization method and the direct method. The former analyzes the local stability of a non-linear system around an equilibrium point by considering its linear approximation, whereas the latter draws conclusions about non-linear system stability by constructing associated energy like functions and observing their variations with time. A basic limitation of the linearization method is its dependency on the linear space of the system. In case of a spring-mass-damper system, for example, if the motion of the spring starts outside its linear range, the linearization method will no longer be able to predict the precise stability of the system. Because of this inherent limitation, we consider the direct Lyapunov method as a stability criterion in this paper. The basic premise of the Lyapunov direct method lies in the fact that if the total energy of a system dissipates continuously over time, the system should at some point, settle to an equilibrium value. The analysis tool used in this method is the Lyapunov energy function, which has to be strictly positive, unless all its variables are zero, and should monotonically decrease with the variation in variables. Thus, we can say that the energy function of the dynamic system under consideration should be a valid Lyapunov function as well as a positive definite function. A positive definite function can be defined such that for a system $x' = f(x)$ having a point of equilibrium at $x = 0$, a function $V(x)$ is defined as follows:

$$V(x) = 0 \Leftrightarrow x = 0 \tag{12}$$

$$V(x) > 0 \Leftrightarrow x \neq 0 \tag{13}$$

$$\dot{V}(x) \leq 0 \; \forall \; x \neq 0 \tag{14}$$

Then $V(x)$ is said to be a Lyapunov Function candidate and the system is stable in the sense of Lyapunov. It is important to note that multiple Lyapunov Functions may be derived for a single system and the choice of a specific Lyapunov Function directly affects the precision of the obtained results. One of the problems associated with this method, however, is that there is no specific procedure to find the Lyapunov Functions; and experience or physical information about the system dictates this choice.

2. Methodology

This section provides the procedure adopted for the design of current and voltage controllers for an autonomous inverter-based microgrid. These controllers share the active power among various inverters according to their droop characteristics and demonstrate good reactive power sharing. The complete design procedure, according to Lyapunov direct method is shown in Fig. 3, and is described in the following sections:

2.1. Voltage controller

As discussed in the previous section, a Lyapunov function is modelled for a system to use Lyapunov theory for controller design. In the case of a voltage controller, we choose the voltage error function as given below:

$$\boldsymbol{e_v = v_{od} - v_{od_{ref}}} \tag{15}$$

Employing the above error function, the Lyapunov function of the system is modelled according to the widely known kinetic energy model of the system.

$$V_1 = \frac{1}{2} e_v^2 \tag{16}$$

According to the Lyapunov theory, if the energy of a system continuously dissipates over time, the system would at some point reach an equilibrium or stable position. This can be modelled mathematically by differentiating the energy function of the system over time. Also, due to a very small value of the change in reference parameters, the differential of all the reference parameters is assumed to be zero.

$$\dot{V}_1 = e_v \dot{e_v} \tag{17}$$

$$\dot{V}_1 = e_v \left(\dot{v}_{od} - \dot{v}_{od_{ref}} \right) \tag{18}$$

$$\dot{V}_1 = e_v \left(\omega v_{oq} + \frac{1}{C_f} i_{ld} - \frac{1}{C_f} i_{od} \right) \tag{19}$$

Since the voltage controller sets the reference for the current controller, we utilize this relationship between the two controllers and set

$$i_{ld_{ref}} = i_{ld} \tag{20}$$

Hence, (20) can be rewritten in the form of reference inductor current as:

$$\dot{V}_1 = e_v \left(\omega v_{oq} + \frac{1}{C_f} i_{ld_{ref}} - \frac{1}{C_f} i_{od} \right) \tag{21}$$

To design the controller, the derivative of energy function defined in (21) should be negative definite. This is possible only if i_{ldref} is modelled as follows:

$$i_{ld_{ref}} = i_{od} - \omega C_f v_{oq} - K_1 e_v \tag{22}$$

Here, a positive gain value K_1 is introduced so that the resulting energy function after this substitution i.e.

$$\dot{V}_1 = -K_1' e_v^2 \tag{23}$$

is guaranteed to be negative definite, and $K_1' = K_1 / C_f$.

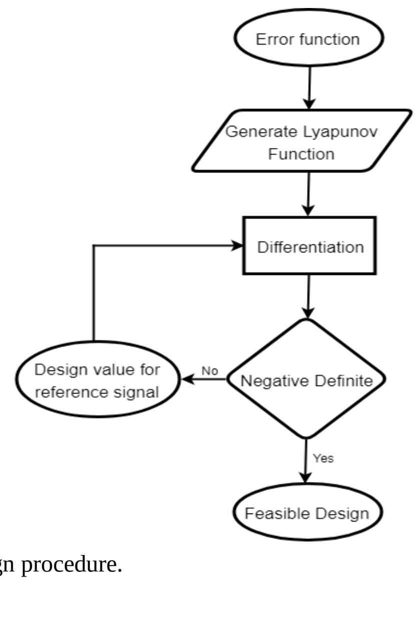

Fig. 3. Flowchart for controller design procedure.

2.2. *Current controller*

Following the same procedure as for the voltage controller, the error function is defined in the form of inductor current error as:

$$e_i = i_{ld} - i_{ld_{ref}} \tag{24}$$

Differentiating the energy function yields

$$\dot{V}_2 = e_i \dot{e}_i \tag{25}$$

$$\dot{V}_2 = e_i \left(\dot{i}_{ld} - \dot{i}_{ld_{ref}} \right) \tag{26}$$

$$\dot{V}_2 = e_i \left(\omega i_{lq} + \frac{1}{L_f} v_{id} - \frac{1}{L_f} v_{od} - \frac{r_f}{L_f} i_{ld} \right) \tag{27}$$

The Lyapunov function will take the following form

$$V_2 = \frac{1}{2} e_i^2 \tag{28}$$

To design the controller, the derivative of the energy function defined in (28) should be negative definite. This is possible only if v_{idref} is modelled as follows:

$$V_{id_{ref}} = V_{od} - \omega L_f i_{lq} + r_f i_{ld} - K_2 e_i \tag{29}$$

Here, a positive gain value K_2 is introduced so that the resulting energy function after this substitution i.e.

$$\dot{V}_2 = -K_2' e_i^2 \tag{30}$$

is guaranteed to be negative definite, and $K_2' = K_2 / L_f$.

3. Results and Discussions

The proposed voltage and current controllers are evaluated using an islanded microgrid that contains two inverter-based DERs. The system parameters are shown in Table 2. The value for V_n is chosen to be 220V RMS per phase and a frequency of 50 Hz is used. A resistive load of 10kW is employed as a test system. Figs. 4-7 show the active power, reactive power, the reference voltage generated by the droop controller and the actual voltage of the two DERs, color coded in red for DER1 and in blue for DER2, for the conventional PI controller based current and voltage controllers presented in [5].

The results obtained from the proposed Lyapunov theory-based current and voltage controllers are shown in Figs. 8-11, in the same order as described previously. Here, a value of 100 is used for K_1 and K_2 in the controller implementation. It can be observed that for the proposed controllers, the settling time and percentage overshoot of the system has significantly improved, as reported in Table 1, whereas the steady state value has been maintained. These two specifications along with the methodological approach towards controller design render the Lyapunov theory-based voltage and current controllers superior to the conventionally used controllers in literature.

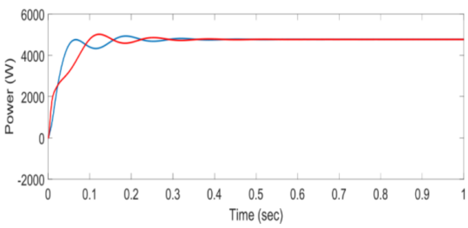

Fig. 4. Active Power: Conventional PI Controller

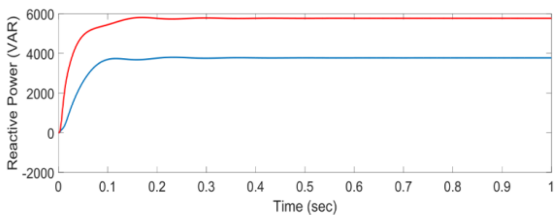

Fig. 5. Reactive Power: Conventional PI Controller

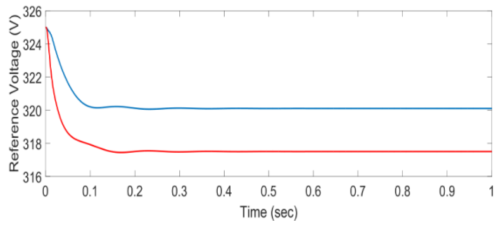

Fig. 6. Reference Voltage: Conventional PI Controller

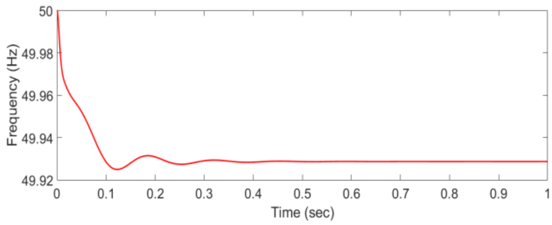

Fig. 7. Frequency: Conventional PI Controller

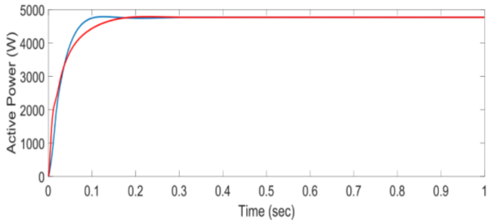

Fig. 8. Active Power: Proposed Controller

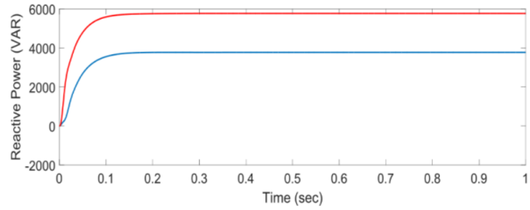

Fig. 9. Reactive Power: Proposed Controller

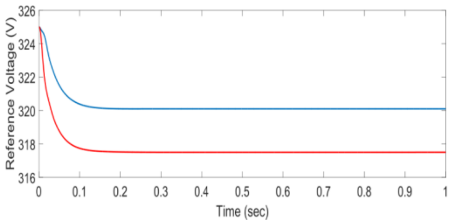

Fig. 10. Reference Voltage: Proposed Controller

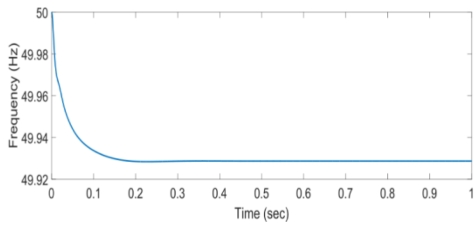

Fig. 11. Frequency: Proposed Controller

Table 1. Settling time of parameters

Parameter	PI Controller (sec)	Proposed Controller (sec)
Active Power (P)	0.3	0.1
Reactive Power (Q)	0.2	0.1
Reference Voltage (V)	0.15	0.15
Frequency (f)	0.05	0.03

Table 2. System parameters

Parameter	DG1 Value	DG2 Value
m_p	0.000094	0.000125
n_q	0.0013	0.0015
R_c	0.03 Ω	0.03 Ω
L_c	0.35 mH	0.35 mH
R_f	0.1 Ω	0.1 Ω
L_f	1.35 mH	1.35 mH
C_f	50 μF	50 μF

4. Conclusion

This paper proposes a new approach for the design of primary voltage and current controllers employed in inverter-based microgrids. The design process, based on Lyapunov direct method, provides a systematic approach for the design of these controllers and has shown promising results in terms of lower settling time and percentage overshoot, and zero steady-state error. The proposed controllers, if integrated in the inverter design, would highly improve the control scheme performance in terms of response speed and the objectives of adequate power sharing and voltage regulation. The proposed methodology can also be employed for designing secondary and tertiary controllers for inverter-based microgrids.

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