Unified model for droop control inverters operated in microgrid

View the article online for updates and enhancements.

Unified model for droop control inverters operated in microgrid

Zhiguo Yan[1,4], Changhua Zhang[2] and Xin Chen[3]

[1] Dongfang Electric Chengdu Intelligent Technology Co.Ltd, Chengdu 611731, Sichuan Province, China;
[2] School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, China;
[3] School of Automation, Chongqing University of Posts and Telecommunications, Chongqing, China.

[4] Email: yanzg@dongfang.com

Abstract. Inverter is widely used in microgrids. Inverter's control strategy plays very important role for its performance and system stability. Several control strategies are proposed, such as droop control, robust droop control and virtual synchronous generator (VSG) control. In microgrid, inverters manufactured by different factories with different control strategies work together. This situation is not good when modelling, analysing and managing microgrid. It naturally rises a question: could these controllers be unified as a unified one? Although some comparisons have been made and proved they have some common characteristics, but there lies no explicit unified controller. In this paper, after investigation of three most common inverter control strategies in microgrid, the unified inverter model is proposed. Simulation results via MATLAB/Simulink software prove that the proposed unified model can be used to represent other three inverters' controllers. A microgrid scheme is used to explain application of the unified model. This research will benefit the design of inverter control strategy and simplify microgrid modelling.

1. Introduction

In recent decades, for alleviating energy and environment crises, more and more renewable energy sources (RESs) have been connected to power grid or combined and operated together as a microgrid [1]. Within the microgrid, electric power generation devices with different working principles will work together. Because of the variety of RES, types of generation devices are also various, such as synchronous generator (SG), asynchronous generator (ASG), or inverter. The inverter is used to transfer direct-current (DC) power into alternating current (AC) power [1] - [2]. With different control strategies, inverters have different performances. Thus for one microgrid, there are maybe tens of inverters with different control strategies working together at the same time. This situation brings obstacles to microgrids's modeling, analysis and management, although in respect of scale, microgrids are extremely small.

SG is main generation device in giant power grid. For the SGs, numerous work have made on their designs, analysis, test and manufacture in the past 100 years [3]. Considerable mature theories and technologies are well built and applied skillfully. By contrast, research about inverter is still in its early stage. According to inverter's structure, inverter can be divided into three parts: power electronic

switch circuit, LC/LCL filter, and controller. Power electronic switch circuit is responsible for electrical energy transfer, i.e. from DC power to AC power. LC/LCL filter is used to eliminate current ripple within its output current. These two parts are relatively mature. The third part is the most flexible. Droop controller is maybe the most famous one because it is able to participate the microgrids' frequency and voltage regulations actively. This is a valuable feature for autonomous operation microgrid [1]. However, droop controller has nearly zero inertia which is important for power system frequency stability [3]. Therefore, kinds of improved droop controllers, such as virtual synchronous generator (VSG) [4] or virtual synchronous machine [5], or synchronverter [6], have been proposed through mimicking role of SG rotor to slow down inverters' response speed. Some further improvements, such as bounding frequency and voltage range to enhance stability [7], raising load sharing accuracy [8], or forcing inverter's dynamic response absolutely equal with that of SG [9], have also been presented. Although these achievements push research of the inverter forward, but they also make inverter control more and more complex. Imagine that for one microgrid, if inverters are taken different control strategies, it should meet great difficulties when modeling, analyzing, and managing the system. Naturally, an idea to unify these controllers occurs. Some works had already done. In [10- 12] dynamic characteristics between VSG and droop controller are compared. The latest research in 2018 concludes that droop control is one kind of VSG with less inertia [12]. But all these comparisons neglect the robust droop controller which presented in [8]. According to our research, advantages of the robust droop controller are not only high accuracy for power sharing between parallel-working inverters, but also convenience for bus equivalence when calculate system power flow. Thus it is an extremely attractive control strategy for inverter operated in microgrids. Thus in this paper, equivalence relationship between VSG, robust droop controller and original droop controller (droop controller in [1] is renamed as original droop controller, for differentiating from the robust droop controller), is investigated. A unified controller is proposed and it benefits to simplify microgrids modeling problem.

The following part of this paper is organized as follows. In section II, mathematical models of VSG, robust droop controller and original droop controller are introduced. In section III, equivalence investigations of them and the unified model are brought out. In section IV, simulation results are provided to demonstrate validity of unification. Finally, conclusions and an outlook are made in last part.

2. Principles of droop controller, robust droop controller and VSG

Here firstly introduce basic structure of inverter, and then list three controllers, using control block diagram.

2.1. Structure of the Inverter

Generally, structures for inverter operated in microgrid are less different. As shown in Figure1, the inverter is interfaced with microgrids at PCC (point of common coupling), through a transmission line Z_{line}. There is LC or LCL filter connected power electronic switch circuit and Z_{line}. u_C is voltage on capacitor, and i_L is current passing through inductor L. u_C and i_L are detected voltage and current values via corresponding sensors and sent to controller, which is commonly a DSP (Digital Signal Processer) chip, where a specialized control algorithm is running. The controller generates PWM (Pulse Width Modulation) drive signals v_r to control power electronic switches. Loads, other microgrid inverters, or even the bulk power grid, are also connected with the inverter through PCC.

In general, control algorithms running in DSP chips are different. There are three most common control algorithms, as following parts listing.
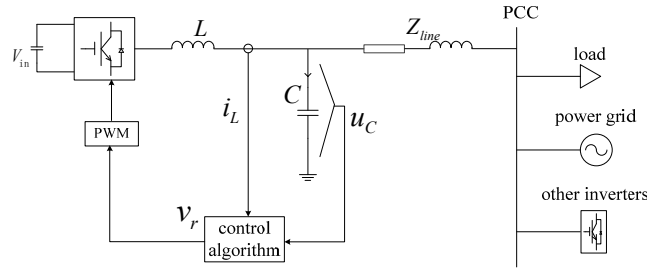
Figure 1. Structure of the inverter with controller.

2.2. Original droop controller
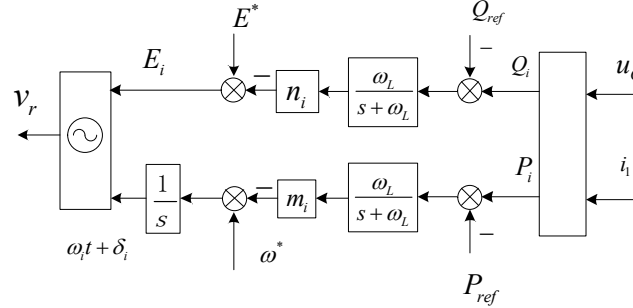This kind controller is proposed in [1], just like that in Figure 2.

Figure 2. Original droop controller.

where, E^* and ω^* are referenced values of voltage amplitude and angular frequency, respectively. m_i and n_i are droop coefficients. P_i and Q_i are output active and reactive power of the inverter. P_{ref} and Q_{ref} are their referenced values. ω_L is cut-off frequency of low pass filter, which reduces ripples of calculated values of P_i and Q_i. Control block diagram in Figure 2 can be rewritten as:

$$E_i = E^* - n_i \left(Q_i - Q_{ref} \right) \qquad (1)$$

$$\omega_i = \omega^* - m_i \left(P_i - P_{ref} \right) \qquad (2)$$

$$\omega_i t + \delta_i = \int \left(\omega^* - m_i \left(P_i - P_{ref} \right) \right) d(t) \qquad (3)$$

In the above equations, Eq. (1) describes droop relationship between inverter's output reactive power Q_i and its terminal open circuit voltage amplitude E_i. Droop here means it has ability to adjust output reactive power when regulates its terminal voltage. For instance, once the value of Q_i increasing, the amplitude of E_i will decrease in a linear way. According to knowledge of electrical circuit, amplitude of inverter terminal voltage u_C will decrease automatically. This is why this controller is called droop controller, and n_i is called reactive power droop coefficient. Similarly, Eq. (2) presents droop relationship between values of angular frequency ω and inverter's output active power P_i. It also means that if microgrid frequency is descending, inverters will automatically increase its output active power and try to lift system frequency up to its rated value. This is quite a good feature for microgrid autonomous operation, and makes droop controller well-known.

2.3. Robust droop controller
Robust droop controller can be looked as an improvement of the droop controller [8]. Figure 3 presents its control diagram. V is amplitude of terminal voltage u_C. K_e is a gain coefficient. Other symbols have same meanings with that in Figure 2.

As the author claimed in [8], the robust droop controller takes inverters terminal voltage V into consideration and imports an extra integrator in voltage V and reactive power Q part. This not only

increases accuracy of power sharing when multi-inverters work in a parallel way, but also reduces fluctuations of the drive signal v_r which usually caused by kinds of disturbances. Compared with the original droop controller, it's easy to find that they are similar in P - ω part and different in V - Q part, just like that shows in Eq. (4):

$$E_i = \int \left[K_e \left(E^* - V \right) - n_i \left(Q_i - Q_{ref} \right) \right] d(t) \tag{4}$$

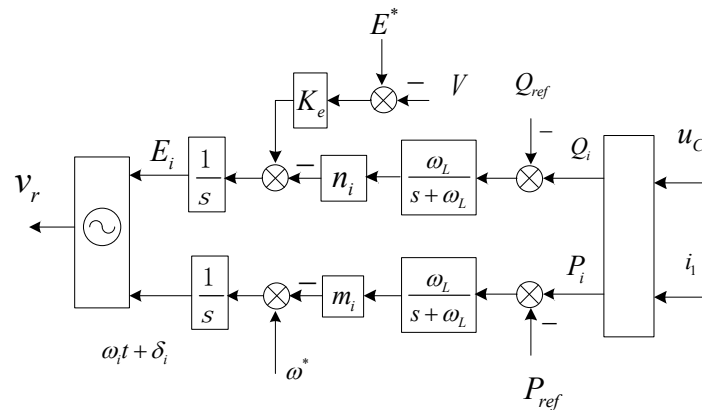So, Eq. (2), (3), (4) are mathematic description of the robust droop controller.

Figure 3. The robust droop controller.

2.4. VSG controller

As to VSG controller, there are several schemes proposed in [4- 5]. One common point for these VSGs is that they introduce SG's rotor swing equations to slow down change speed of phase of PWM modulation waves. Thus seemingly VSG has a so-called virtual inertia and this benefits system frequency stability. It should be noted that some VSG controllers take a double-loops structure. Generally current loop is taken as inner loop and power loop as outer loop. But some other VSGs have only outer power loop. For simplicity, because inner current loop always has a much faster response speed than that of outer loop, when analyzing system stability or low frequency oscillation, it is reasonable to ignore the dynamics of inner loop. Therefore, a single loop VSG controller in Figure 4 is selected to delegate the VSG controllers [10]. Although it has no inner current loop, but this has less adverse effect on the conclusions of this paper because the other two controllers also have no inner current loop. In other words, if the robust droop controller and original droop controller supplement the inner current loop, another improved unified model can also be obtained. Thus taking single-loop VSG controller to delegate double-loops VSG controller is reasonable.
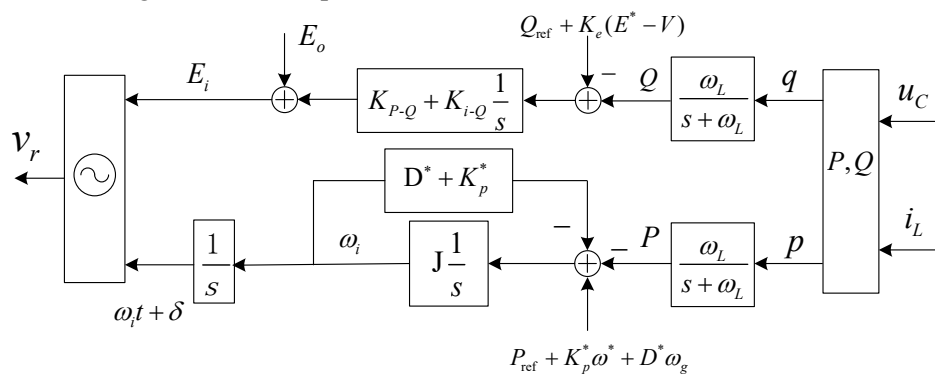

Figure 4. VSG controller.

where, E_0 is a feed forward component which can speed up dynamic response for the VSG to regulate its terminal's voltage. K_{P-Q} and K_{i-Q} are control parameters of PI (proportional-integral) controller which acts on Q–V part of the VSG. K_p^* is a droop coefficient of P-ω part, similar with m_i in Figure 2 & Figure 3. Value of $1/J$ means virtual inertia, which obviously effects inverter's output power response speed. ω_g is microgrids angular frequency. In [10], D^* means damping coefficient which will benefit to obtain higher damping if sets it at a proper value. Other symbols have the same meanings as the previous figures. VSG controller in Figure 4 can be written as the following equations:

$$E_i = E_0 + (K_{P-Q} + \frac{1}{s}K_{i-Q})(Q_{ref} + n_i(E^* - V) - Q_i) \tag{5}$$

$$\omega_i t + \delta_i = J \times \int \frac{P_{ref} + K_P^* \omega^* + D^* \omega_g - P_i}{s + T} d(t) \tag{6}$$

where $T = J \times (D^* + K_P^*)$. This means T is a design parameter, and has nothing to do with parameters of electric circuit.

3. Equivalence analysis and the unified model of three controllers

Compare the Figure 2, 3, 4. It's easy to find these three inverters' controllers have some common features. For example, they all have to calculate values of P & Q, subsequently a first-order inertial unit to eliminate ripples in the calculated values. But differences are also obvious. For example, the latter two inverter controllers take the terminal's voltage V into consideration but original droop controller neglects it. It's the difference that make these inverters have various dynamic characteristics. In order to unify these three controllers, utilize their similarities and reserve their difference within a unified form. Thus the unified VSG controller is presented in Figure 5.
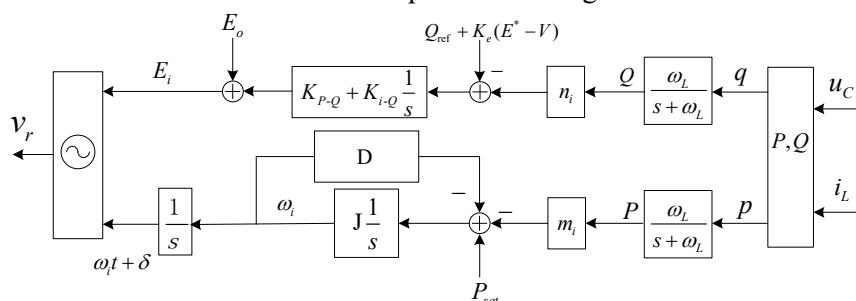

Figure 5. Control diagram of the unified controller.

For example, if E_0, K_{P-Q} set zero, D sets 1 and J sets infinite value, controller in the Figure 5 absolutely equals with the robust droop controller in the Figure 3. Their relationship can be listed as in Table 1:

Table 1. Parameters relationship between unified controller and other three controllers.

Controller type	Parameter value in the unified model
Original droop controller	$E_o = 0$ $K_e = 0$ $K_{P-Q} = 1$ $D = 1$ $1/J = 0$ $K_{i-Q} = 0$
Robust droop controller	$E_o = 0$ $K_{i-Q} = 1$ $K_{P-Q} = 0$ $D = 1$ $1/J = 0$
VSG	$n_i = 1$ $m_i = 1$ $D = D^* + K^*$ $P_{set} = P_{ref} + K_p^* \omega^* + D^* \omega_g$

From above discussion, a conclusion can be drawn that the VSG, robust droop controller and original droop controller, are naturally homogeneous controllers. Thus when these inverters work in the same microgrids, taking the unified controller to model their characteristics will simplify procedure of system modeling and analysis.

4. Simulation results

4.1. Effectiveness of the unified model

Via MATLAB/Simulink software, simulation work is conducted to validate effectiveness of the unified controller. For simplicity, here take equivalence of original droop controller and the unified controller as an example. System topology is shown in Figure 1. There lies a disturbance. Voltage amplitude on PCC drops 10% at t=2.8s and restores at t=3.0s. Main parameters of the system are given in Table 2:

Table 2. Simulation parameters.

Parameter	Value	Parameter	Value	Parameter	Value
Rated voltage $Vrms$	380V	E^*	1.05pu	Filter resistance R_f	0.1Ω
Rated power Sn	50k VA	E_0	0	Filter inductance L_f	2.8mH
Rated grid frequency f_n	50 Hz	D	1	Filter capacitance $C\mu$	13μF
Tramsmisson line inductance X_{line}	0.077Ω	K_{i-Q}	0	Droop coefficient m	0.01
Tramsmisson line resistance R_{line}	0.225Ω	Q_{ref}	0	Droop coefficient n	0.1
Virtual inertia $1/J$	0.0001	Ke	0	$Pset$	0.6 pu
K_{p-Q}	1				

The simulation results are shown in Figure 6. It's easy to find that two curves (red line means output P of original droop controller; blue dash line is for the unified controller) absolutely overlapping even disturbance occurring. This simulation proves that the unified controller can absolutely equal with the original droop controller if set its parameters certain values. Thus when model the microgrid, we can use the unified controller to replace the original droop controller with less accuracy loss.
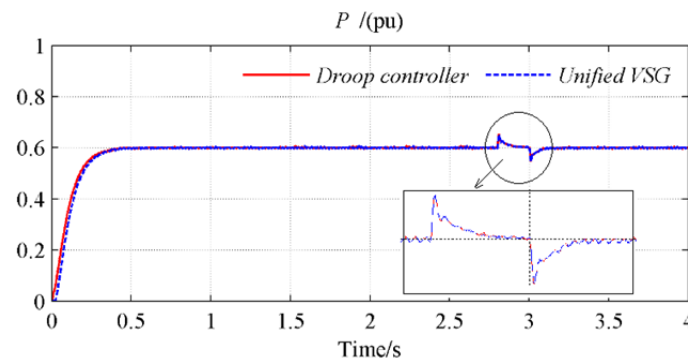

Figure 6. Simulation curves of droop controller and unified controller.

4.2. Application of the unified controller

In order to present application purpose of the unified controller, the microgrids with two inverters is shown in Figure 7, where inverter 1 takes original droop controller as its control strategy and the other one takes the robust droop control strategy. For both inverters, P-ω droop coefficient m is 0.01 and Q-V droop coefficient n is 0.1. When we model the system to analyze its small signal stability, according to paper [13], two mathematical models for inverter 1 &2 should be built respectively. But because inverter 1 &2 take different control strategies, thus their corresponding models have different forms. For example, when analyzing microgrid small signal stability, usually a three-order model is enough for original droop controller to depict its dynamics, whereas a six-order model for the robust droop controller. If there are tens of inverters takes different control strategies, their models should have different orders and thus generates difficulties to model them. By contrast, if use the unified model to

stand for these controllers, we can obtain their models in a uniform way. This will simplify the process of program to analyze the system stability, and outstand the difference between these controllers.
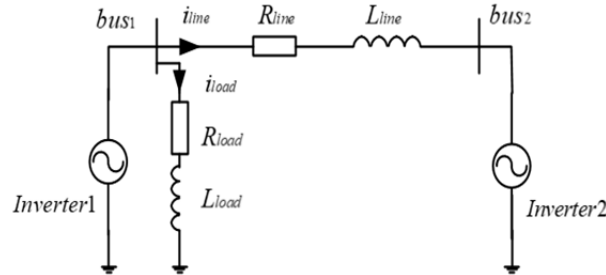

Figure 7. A microgrids system with two interconnected inverters.

For the above two-inverter system, Table 3 shows system parameters and its initial states.

Table 3. System parameters and initial states for two-inverter microgrids

Parameter	Value	Parameter	Value	Parameter	Value
$R_{line}(\Omega)$	0.092	L_{line}(H)	$2e^{-4}$	L_{load} (H)	$2e^{-4}$
$R_{load}(\Omega)$	5	δ_0(rad)	-0.0052	ω_{com0}(pu)	1.0029
$i_{d0,1}$ / $i_{d0,2}$(pu)	0.2914/0.2921	$i_{q0,1}$ / $i_{q0,2}$(pu)	0.0010/0.0021	i_{loadd0}(pu)	0. 5773
$e_{d0,1}$ / $e_{d0,2}$(pu)	-0.0834/-0.0848	$e_{q0,1}$ / $e_{q0,2}$(pu)	1.0523/1.0571	i_{loadq0}(pu)	0.0590
$E_{t0,1}$ / $E_{t0,2}$(pu)	1.054/1.055	i_{lined0}(pu)	0.0197	i_{lineq0}(pu)	-0.2865

In the literature [13], the methods are given to model the system in Figure 7 and then calculate its eigenvalues for stability analysis. Here we can model the inverters in the microgrids with its original controllers and the unified controllers. Then compare eigenvalues obtained by these two methods. Table 4 shows eigenvalues calculated by two kinds of models. Values in the first and third columns are eigenvalues obtained by use of the controller's original forms, and values in the second and fourth columns are eigenvalues obtained by use of the unified models. It's easy to find that the unified models have enough accuracy for the eigenvalue calculation.

Table 4. Comparison of eigenvalues obtained by the two models

Eigenvalues with the original models	Eigenvalues with the unified models	Eigenvalues with the original models	Eigenvalues with the unified models
0	0	-5.0913	-5.1341
-50	-50	-2000.0001	-2000.0009
-50	-50	-1457.2157 ±2654.3613 j	-1456.2835 ±2700.6636 j
-49.9913	-49.9987	-1456. 7913 ±3214.1475j	-1455.9997 ±3329.2898j
-49.5871	-49.0841	-334.3164 ± 8894.2374j	-330.3446 ± 9283.3012j
-43.6154	-44.6437	-334.3013 ±9789.4744j	-330.3505 ±9912.0742j
-25.2751 ±19.7624 j	-24.8579 ±18.6635 j	-	-11841.9651 ±314.7657 j
-12.0247	-11.8371	-	-19719871.4272 ±314.6145j
-9.7713	-9.4769	-	-51618718.8086 ±314.6211j
-48.1285 ±314.1737 j	-47.5538 ±314.1707 j	-	

5. Conclusions

In this paper, for three widely-used inverters controllers in microgrids, through investigating their control diagrams, conclude that they are homogeneous controllers and propose their unified controller. Simulation results via MATLAB/Simulink software prove effectiveness of the conclusion. This unified model will be helpful for inverter controller's design and stability analysis. The microgrids scheme with two different inverter's controllers is used to explain application purpose of the unified model which simplify the process of program. Because it's proved that all three inverters' controllers have the same form, it's easier to compare these inverters' dynamic characteristics. For example, according to Table 1, we know that the difference between original droop controller and robust droop controller are reflected in the different values of the parameters Ke, $K_{p\text{-}Q}$, and $K_{i\text{-}Q}$. Thus the comparison between the dynamics of these two controllers turns into the comparison of values of Ke, $K_{p\text{-}Q}$, and $K_{i\text{-}Q}$. The next work is to use the unified model to investigate interaction between different inverters and find the most proper controller type for low voltage microgrid.

References

[1]   Lasseter R H 2002 "Microgrid," in *proc. Power Engineering Society Winter Meeting* **1** 305- 308
[2]   Euzeli Cipriano, Cursino Brandão Jacobina, et al 2012 "Single-Phase to Three-Phase Power Converters: State of the Art," *IEEE Transactions on Power Electronics* **27(5)** 2437 - 2452
[3]   P. Kundur, *Power system stability and control*, New York, McGraw-Hill, 1994.
[4]   J Driesen and K Visscher 2008 "Virtual synchronous generators," in *Proc. IEEE Power Energy Soc. Gen.Meeting—Convers. Del. Elect. Energy 21st Century* 1–3
[5]   Y Chen, R Hesse, D Turschner,H-P Beck 2011 "Improving the grid power quality using virtual synchronous machines," in *Proc. Int. Conf. Power Eng. Energy. Elect. Drives* 1–6
[6]   Q.-C Zhong, G. Weiss 2011 "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron* **58(4)** 1259–1267
[7]   Qing-Chang Zhong, George C. Konstantopoulos, et al 2016 "Improved Synchronverters with Bounded Frequency and Voltage for Smart Grid Integration," *IEEE Transactions on Smart Grid*, vol. PP, Issue: **99** 1–1
[8]   Q-C Zhong 2013 "Robust droop controller for accurate proportional load sharing among inverters operated in parallel," *IEEE Trans. Ind. Electron* **60(4)** 1281–1290, Apr 2013
[9]   Changhua Zhang, et al 2013 "An Improved Synchronverter Model and its Dynamic Behaviour Comparison with Synchronous Generator" [C], *2013 IET Renewable Power Generation Conference*, Beijing, China, 9-11 Sep
[10]   Jia Liu, Yushi Miura, et al 2016 "Comparison of Dynamic Characteristics Between Virtual Synchronous Generator and Droop Control in Inverter-Based Distributed Generatros," *IEEE Trans. Power Electron* **31(5)** 3600–3611
[11]   Xin Meng, Zeng Liu, Jinjun Liu, et al 2017 "Comparison between inverters based on virtual synchronous generator and droop control ", *IEEE Energy Conversion Congress and Exposition*, Cincinnati **1-5** 4077 - 4084
[12]   Vinu Thomas, S. Kumaravel, S. Ashok 2018 "Virtual synchronous generator and its comparison to droop control in microgrids ", *International Conference on Power, Instrumentation, Control and Computing (PICC)*, Thrissur **18-20** 1–4
[13]   N Pogaku, M Prodanovic,T C Green 2007 "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," IEEE Trans. Power Electron **22(2)** 613–625