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Inverter Model and Control Strategies for Single-Phase Rooftop Photovoltaic in Unbalance Three–Phase Residential Network

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Abstract

The installation of single-phase rooftop photovoltaic (PV) are growing world widely, which have several benefits and drawbacks in residential low voltage (LV) distribution system. In one hand, this distributed generation (DG) is easy to install, has low maintenance costs, and subsidies in price. On the other hand, as PVs are installed, without controlling their ratings and locations it may deteriorate the overall grid performance including reversed power flows, high losses and unacceptable voltage profiles. This paper proposes modelling and controlling strategies for grid-tied, rooftop PV inverters that address some concerns of high penetration PV while also adding several benefits to the utility. The modelling strategy contains of a proper inverters' control, which is developed in order to extract the maximum amount of the photovoltaic generator. The control strategy does not require an advanced communications infrastructure, however it allows for several collective controls of active and reactive power outputs of the PV units and their grid-tied inverters. The proposed strategies are simulated in Matlab/ Simulink platform. The results show that the inverters are devouring very less voltage and current harmonic and able to maintain approximately constant voltage profile for highly unbalanced system.

Keywords: Grid-tied rooftop PVs, communication infrastructure, grid-tied inverters, AC three-phase, grid-connected system, and current harmonic

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1. Introduction

Rooftop photovoltaic (PV) cells are commonly used as the commercial distributed generation units (DGs) at customers' side in the residential feeders [1]. They are connected to the network through power inverters. The massive numbers of PVs in the network are able to change the direction of power flow and lead to voltage rise along the feeder. Additionally, most of the residential rooftop PV systems are single-phase units and their integrations into the three-phase networks might also cause unbalance issues due to their random locations and ratings [2].

Power inverter is the key technology of power grid as the interface device between PV and grid. The grid inverter plays a fundamental role in the energy development and utilization, affecting the economics and reliability of the PV-grid generation system straightforwardly. Then, the improvement of inverter work performance and power generation and distribution quality become the focus of research in recent years [3].

This paper is discussing the model and control strategies of PV inverter that addresses the penetration of PV while accumulating its benefits to the unbalanced three-phase low voltage (LV) residential feeder. The proposed strategies are simulated in Matlab / Simulink and results show that the inverters are consuming very less voltage and current harmonic and able to sustain nearly constant voltage profile for highly unbalanced system.

2. Related Works

Several previous studies have been performed to evaluate the potential impact of PV inverters. Firstly, the studies have discussed some important distributed PV-grid interaction issues, then they also have discussed recent grid standards related to connection of PV inverters into the LV distribution networks are mentioned to realize network limitations, followed by the discussions regarding the voltage support methods proposed so far to increase PV hosting capacity of LV networks. Eventually, the advantages and disadvantages of reactive power methods are summarized.

In reference [4], it states that the primary function of a PV inverter is to inject current synchronized with the grid where its magnitude depends on available PV power on the dc side and its angle with referenced to the grid voltage is adjusted in such a way that unity power factor is achieved unless reactive power service is requested by local network operator. Furthermore real power injection, secondary functions such as static reactive power service low voltage fault ride-through (LVRT), real power curtailment, voltage

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unbalance correction can be added as ancillary services for providing reliable operation of distribution networks.

References [5] and [6] discuss the modelling and control strategy of PV inverter system that meets the LV distribution code requirement in Denmark and German, respectively. As the model and control strategy applied, the behaviour of short-term grid disturbances are being monitored due to control the derivation of inverter system for PV application in three-phase unbalance feeder.

Other study that discusses the impact of PV in the LV distribution network in New Zealand is presented in [6]. This study presents a case of simulating the entire LV network from a single utility, comprising 11kV–415V transformers and their associated distribution feeders. The results show power flow by network type and the effect of using PV inverters with voltage regulation.

3. Proposed Schemes

At noon periods, rooftop PVs usually generates their maximum power while the load demand in the network is at its minimum level. The high penetration of rooftop PVs can cause voltage rise in the network and force the voltage to exceed the maximum allowable limits. The injected reactive power and curtailed active power approaches can be applied for voltage amplitude control within the network when single-phase PVs are installed unequally at different phases and locations throughout the network and have different ratings. Fig. 1 shows the flowchart of the analysis of the PV penetration level in certain LV network.

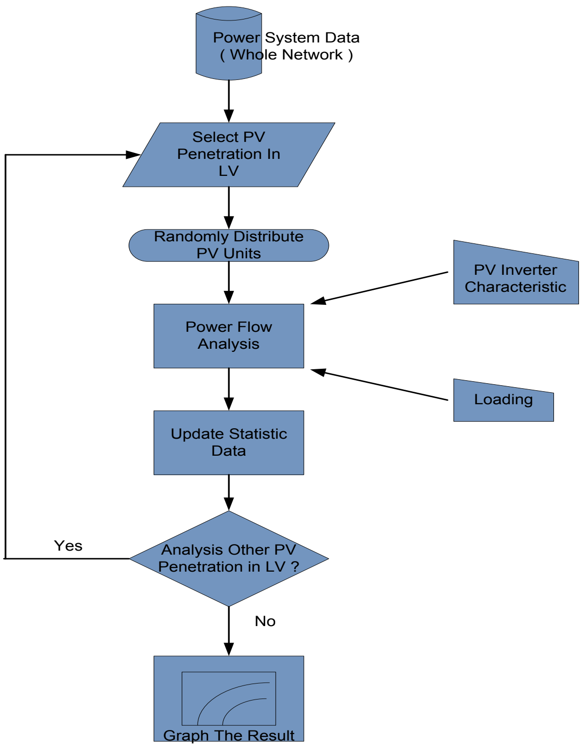

Fig. 1. Flowchart to analyze the PV penetration level in certain LV network.

3.1. Network under consideration

Consider a 20kV three-phase medium voltage feeder supplying a 380V three-phase four-wire low voltage residential feeder, as shown in Fig. 2. The residential feeder is assumed to be unbalanced due to the distribution of loads and unequal distribution of single-phase rooftop PVs with different ratings.

Reference [7] shows the possibility of utilizing the distributed reactive power support and active power curtailment by rooftop PVs in order to regulate the network voltage profile.

3.2. Load flow modelling and analysis

An unbalanced sweep forward backward load flow method is developed in Matlab/Simulink and used for the analysis of the three-phase four-wire radial network under consideration. The load flow calculates bus voltages along the feeder. Fig. 3(a) shows the block diagram of the load flow method developed in Matlab/Simulink. In this fig, all the information that is needed to develop sweep forward backward load flow is described.

The branch power flows and bus voltages are updated by crossing between source and end nodes iteratively. Specifying initial bus voltages or flat start, backward sweep step determines the branch power flows and updates the bus voltages by the summation of each load, generator and shunt capacitor currents from end buses toward the source bus. Similarly, by following backward sweep step and starting from the specified source voltage level, forward sweep computes the voltage drop and updates branch power flows along the feeder with its associated laterals. Sweep forward backward load flow repeats in sequence until the bus voltages meet a certain convergence criteria. (Fig. 3(b)). This fig. shows two-bus and single-line representation of distribution networks for the solution of V-I sweep forward backward and load flow algorithm. The load flow calculates bus voltages along the feeder.

3.3. Active and reactive power control of inverter

The PV inverters currently operate in constant output power mode. Under certain conditions, they only inject current with unity power factor and do not affect the voltage at their point of common coupling (PCC). As the inverters are operated in voltage control mode, each PV is able to correct its own PCC voltage to a desired value by injecting or absorbing the required amount of reactive power. To minimize the difference between the PCC voltage with its reference value, each PV inverter needs to exchange reactive power with the feeder o keep the voltage of its output equal to the desired value based on the droop control strategy as in [1].

The structure of PV grid-connected inverter is as shown in Fig. 4 [8]. The system is mainly composed of the former stage of DC-DC converter, intermediate DC bus and the level of DC-AC inverter. The DC-DC converter boosts the DC voltage. Firstly, sample the PV cells output voltage and

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current, and compute the collected signals based on the improved conductivity incremental control algorithm. Then control the switch state of the DC booster circuit to realize maximum power.

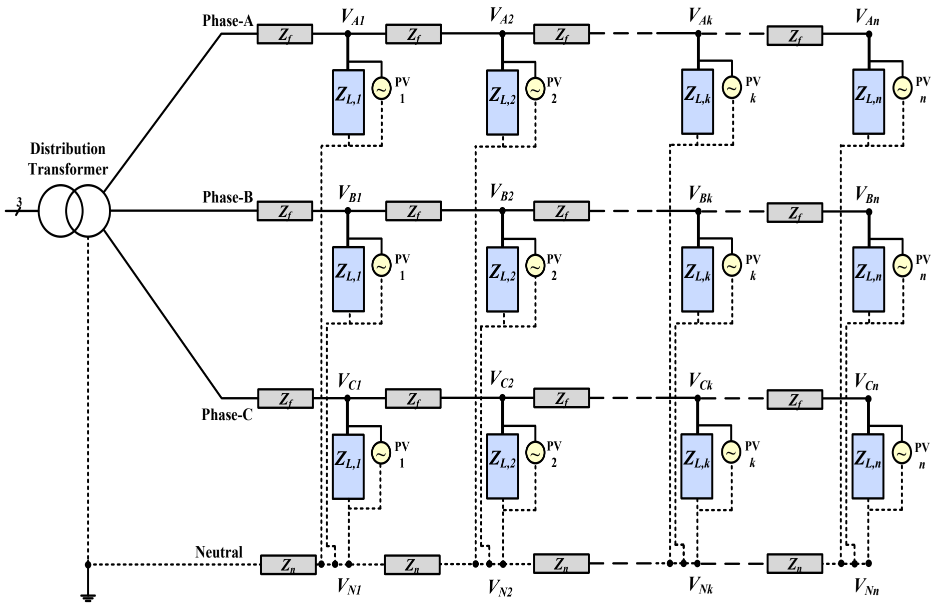

Fig. 2. Single line diagram of the simulated three-phase unbalanced residential LV network with single-phase rooftop PVs.

The only function of the former stage is to realize the multiple power points tracking (MPPT) is in its stage. More over, Fig. 5 shows the model of PV inverter that has been made and run in Matlab/ Simulink. The DC-AC converter implements double PI control. The outer loop maintains DC bus voltage stable, inner loop is used to control the stability of the output current.

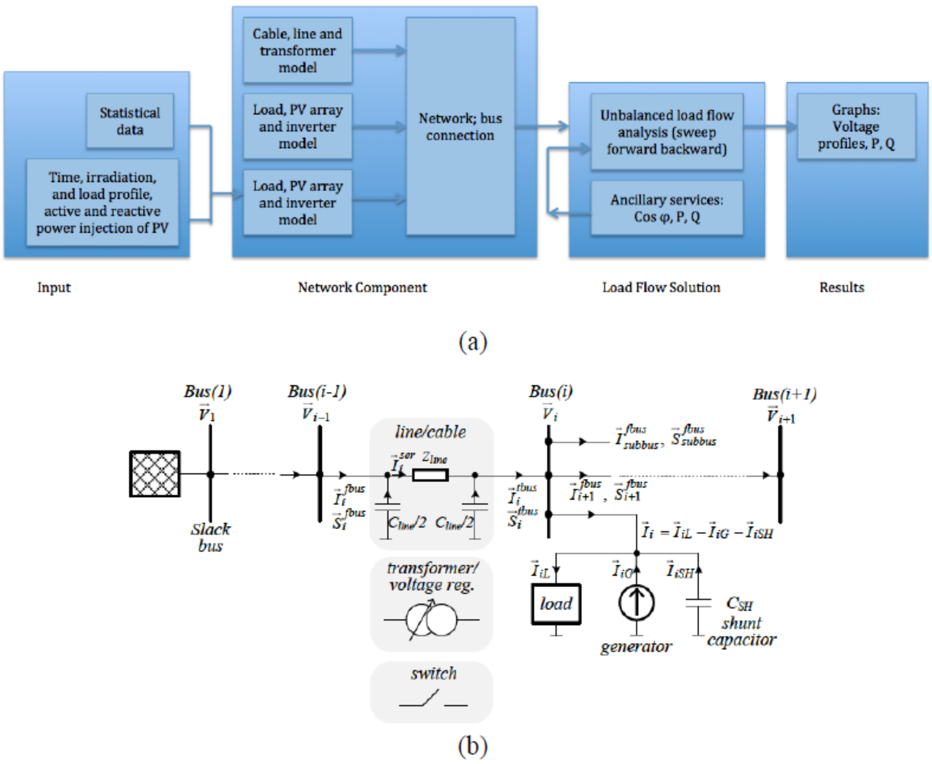

Fig. 3. Load flow development in Matlab/ Simulink; (a). Block diagram. (b). Two-bus and single-line diagram of sweep forward-backward algorithm

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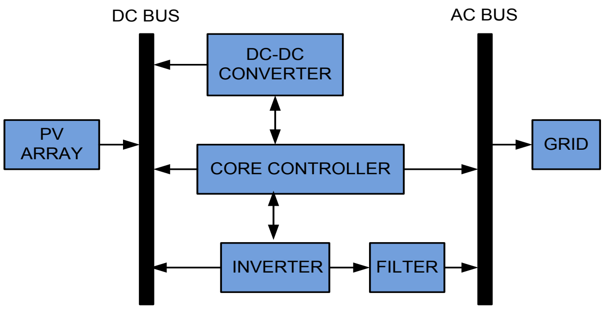

Fig. 4. PV grid-connected inverter controller diagram

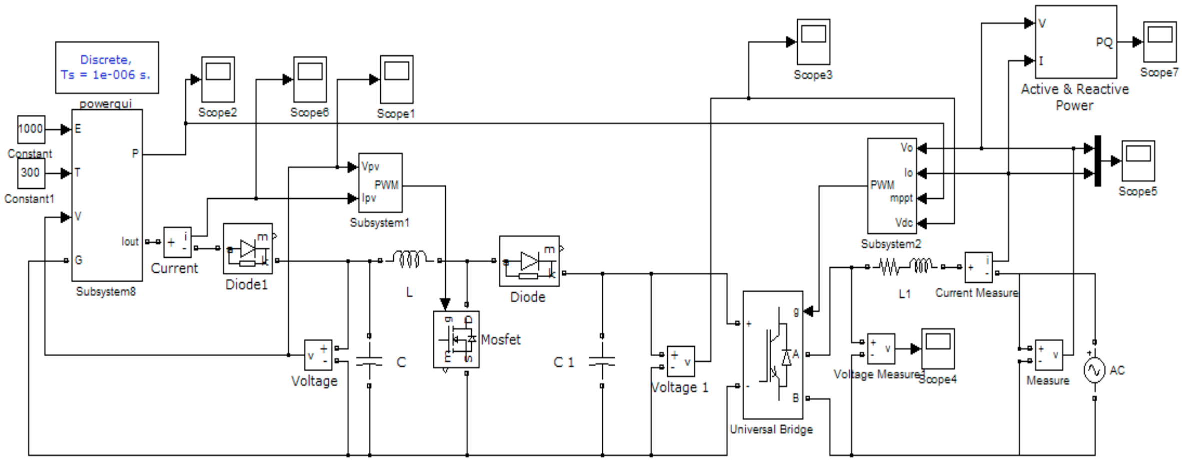

Fig. 5. PV inverter Matlab/Simulink model

4. Simulation Results

The configuration and setting for the grid-connected PV inverter model that is shown in Fig. 5 are as follow, 500 PV cells in series and 1000 in parallel, under the environment temperature of 300K, light intensity 1000W/m^2, the grid voltage 220V, 50Hz, intermediate dc bus voltage 380V, the simulation time is 0.4s, use the PV array model for simulation results. The waveforms of the output voltage, output current and output power of the former DC-DC converter is as shown in Fig. 6(a). The DC-link voltage, AC current and active power of the inverter waveforms is as shown in Fig. 6(b). The output voltage (blue) and current (red) of the line side is as shown in Fig. 7.

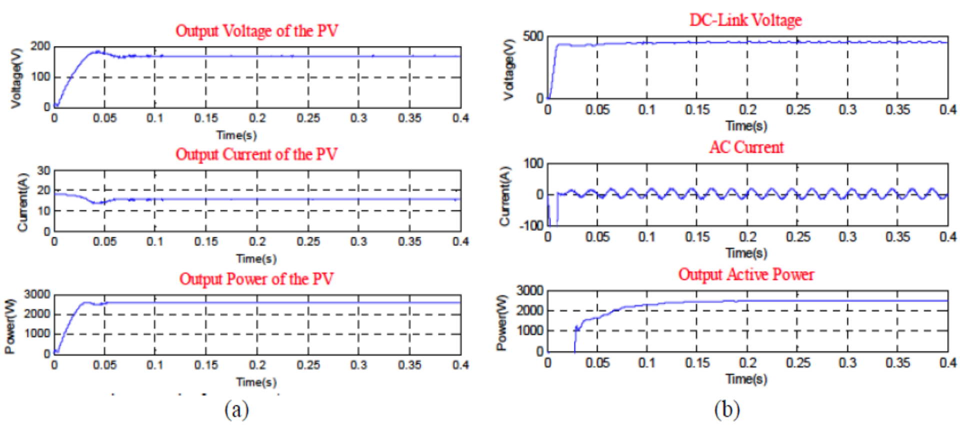

Fig. 6. Output voltage, current and power, respectively of (a) DC-DC converter; (b) Inverter.

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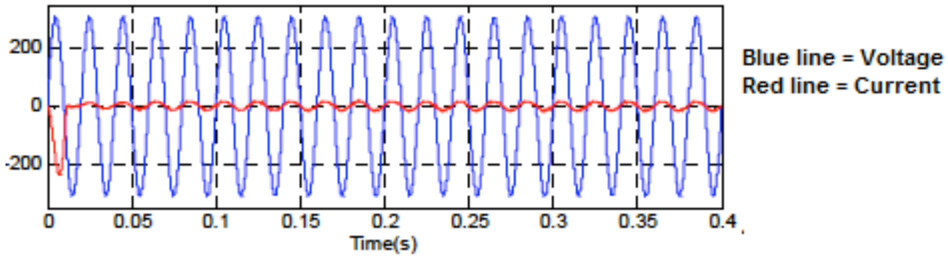

Fig. 7. Output voltage and current of line side.

5. Conclusion

PV grid-connected inverter control structure is made of two level control modes. The DC-DC converter achieve maximum power tracking control, while the inverter maintains the DC bus voltage stable and comprehends the connect grid function. Both couple each other through the intermediate DC bus, constructing the system match simply. The control algorithm has the good rapidity and the stability. The simulation results indicate that the system is stable and has worthy performance. AC bus voltage is around 380V; the PV array output power remains in the maximum power point and achieves a good sinusoidal output wave.

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