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Power flow control strategy for a three-phase four-leg voltage source inverter in a microgrid

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Abstract. In recent years, there has been an increasing interest in three-phase four-leg voltage source inverters (VSIs) due to several benefits that they provide for three-phase four-wire distribution systems and microgrids. This study presents a novel control strategy for a three-phase four-leg VSI in the synchronous reference frame. The challenge is to control the power flow between the utility grid and the microgrid. The proposed control strategy comprises an external power loop and an internal current control loop based on the conventional proportionalCintegral (PI) type controllers. The external power control loop and the internal current loop are, respectively, employed to control the power flow of VSI and to generate the appropriate modulation signals. Also, genetic algorithm (GA) is applied to optimize the current control parameters. An appropriate power flow control between the utility grid and the microgrid is achieved through the proper control strategy during load and set-pint change conditions. The validity of the proposed control strategy is verified through MATLAB /Simulink software environment.

Keywords: microgrid, control, grid-tied mode, inverter, genetic algorithm (GA)

1 Introduction

A microgrid can be defined as a cluster of distributed energy resources (DERs) and loads that interface with distribution networks [8]. DERs are usually connected to the distribution network through power electronic devices in order to provide adequately proper control scheme. Recent developments in green power have heightened the needs of micro-sources such as wind turbines, fuel cells, photovoltaics (PVs) integrated with storage devices and hydro due to their potential to provide high market penetration. The use of micro-sources and green power can also offer significant technical benefits for the power system such as adequate control and power quality.

The microgrid has the ability to operate in both grid-tied and islanded modes[8]. In the grid-tied mode, the microgrid is capable of exchanging power between the microgrid and the utility grid based on a proper economic policy[7]. On the other hand, the microgrid can operate autonomously, whenever a planned action or unplanted power quality events occur in the utility grid. Fig. 1 shows a basic microgrid architecture in grid-tied mode.

Inverters play an important role in control of active and reactive powers in VSIs. The most important role of inverters in grid-tied mode is to control both the active and reactive power between the utility grid and the microgrid[6]. In grid-tied mode, the active and reactive power output values must be adjusted according to pre-specified values. Therefore, the inverter-based distributed generation (DG) units should be operated in a proper power control mode[17]. In this mode, the main purpose is to achieve zero steady- state error, ensuring high

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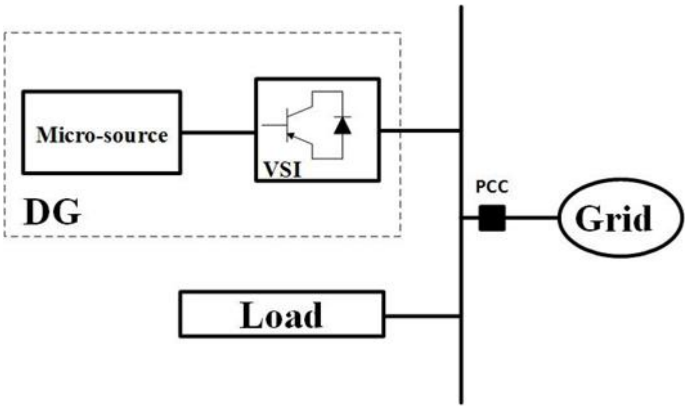

Fig. 1: The structure of a typical grid-tied microgrid

power quality and improving transient response. Hence, it is vital to carry out grid-tied mode with a proper control scheme to attain zero steady-state error in tracking of reference values and fast dynamic response.

Several techniques have been proposed in the literature to control VSIs operating in microgrids. These techniques can be categorized in two main linear and nonlinear groups[3]. The linear control techniques include PI controllers, proportional-resonant (PR), state feedback controllers and predictive control strategies. The second also includes the hysteresis current controller (HCC) and online-optimized controllers[3].

The PR controllers are commonly used techniques in control of VSIs, because they are capable of eliminating steady-state error. However, they cannot cope with varying utility frequency[1]. Also, the HCC is one of the popular control methods, which can work well in control of VSIs[12]. It is noteworthy that the AC current can keep within the limits of a hysteresis band. However, the switching frequency is variable and relies on the load and system parameters in HCC. Moreover, it cannot cope with unbalanced and nonlinear currents. Although in recent years, there has been an increasing interest in nonlinear controller, they are quite complicated. On the other hand, linear techniques such as PI controllers are widely used as they can provide high quality sinusoidal waveform. Linear controllers offer extremely good dynamics, overload rejection and low current ripple[18].

This paper presents a new control strategy for a three-phase four-leg VSI operating in grid-tied mode. The suggested control strategy in each phase contains a power controller and a current control loop based on the conventional PI-type regulators in the dq frame. Furthermore, a feed-forward path is employed in the internal current loop to obtain a better dynamic response. Additionally, GA is used to optimize the current control parameters.

The rest of this paper is divided as follows. Mathematical foundations of three-phase four-leg VSI is explained in section 2. In section 3, the philosophy of per-phase power control strategy in the dq reference frame is introduced and the most suitable orthogonal signal generation (OSG) technique is selected. In section 4, the structure of the proposed control strategy is introduced. In section 5, the appropriate performance of the proposed method is validated by simulation results. Finally, the conclusion is provided.

2 Modeling of three-phase four-leg VSI

The configuration of the four-leg grid-connected inverter and its output LC filter is shown in Fig. 2, V_S is the utility voltage and C is the filter capacitance. It is noteworthy that the neutral point of the model is connected to the fourth leg of the inverter. Moreover, a large capacitance employed as the DC voltage to be constant the voltage[13]. In this work, the sinusoidal pulse-width modulation (SPWM) is considered according to[4].

2.1 Mathematical model

Although controlling three-phase inverters in the dq frame is now a widely used method for three-phase four-leg inverters, it is not as well developed as single and three-phase applications. It is because of the fact

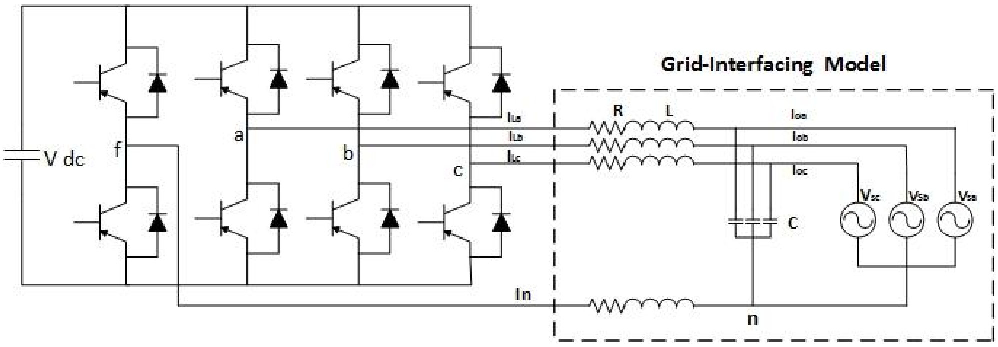

Fig. 2: Three phase four-leg grid-connected VSI model

that each phase must be controlled independently; therefore, per-phase control strategy for four-leg inverters need a secondary orthogonal signal in the dq frame. Several orthogonal signal generation methods have been suggested in the published research to generate an orthogonal signal from an original signal [2, 4, 5, 10, 13, 16]. In this paper, the all-pass filter (APF) is used because of its simplicity[15]. Fig. 3 shows the block diagram of a first order APF, where W_f is the fundamental angular frequency.

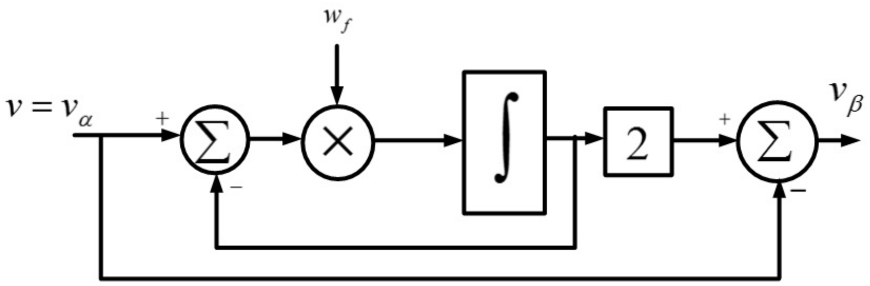

Fig. 3: Structure of first order APF

In order to implement per-phase control strategy based on the orthogonal current components, each phase of the inverter is modeled as an ideal controlled voltage source (E_{inv}) [14]. Fig. 4, shows the model of the per-phase four-leg inverter based on the single-phase calculation. The grid-interfacing model connected to that phase of inverter can be introduced by a voltage source (V_s), and i_l and V_c, respectively, represent the current of the inductor and the voltage of the capacitor.

By using the Clark transformation, the equations of the system in Fig. 4, in the stationary reference frame can be obtained as:

$$l\frac{di_{l\alpha\beta}}{dt} = e_{inv\alpha\beta} - i_{l\alpha\beta}R - v_{c\alpha\beta}. \tag{1}$$

By using the Park transformation, the equations of the system in Fig. 4 in the synchronous reference frame can be obtained as[7]:

$$\begin{pmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{pmatrix} = -\frac{R}{L}\begin{pmatrix} i_d \\ i_q \end{pmatrix} + \frac{1}{L}\begin{pmatrix} e_d \\ e_q \end{pmatrix} - \frac{1}{L}\begin{pmatrix} v_d \\ v_q \end{pmatrix} + w\begin{pmatrix} i_q \\ -i_q \end{pmatrix}. \tag{2}$$

Where w is the coordinate angular frequency.

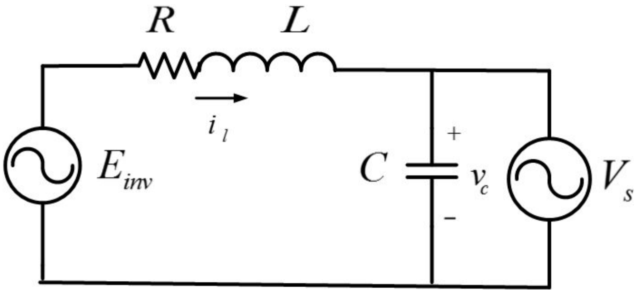

Fig. 4: The basic model of per-phase four-leg inverter

3 Control system structure

This section introduces the novel per-phase control strategy for the three-phase four-leg grid-tied inverter. As shown in Fig. 5, the control system structure in each phase contains a power control loop, an internal current control loop, and GA block. In this figure, V_{ca} and Ica are the α phase voltage and current of the filter capacitor, respectively. As indicated in Fig. 5, the components are created by α to $\alpha\beta$ transformation block as a real per-phase component. On the contrary, the β components are created from a fictive circuit by the APF. A simple phase-locked-loop (PLL) is also applied to detect the voltage phase angle. As seen in Fig. 5, the current of the capacitor is applied as a feed-back in the current controller, as it rejects the disturbance better than inductor current[13]. It is owing to the fact that the current of the capacitor is directly proportional to the time change of output voltage. Consequently, it provides a better prediction in term of voltage distortion[13]. Feed-forward (FF) loop also is applied to avoid the coupling between active and reactive power. Furthermore, the conventional PI-type controllers are used for the power and current controllers.

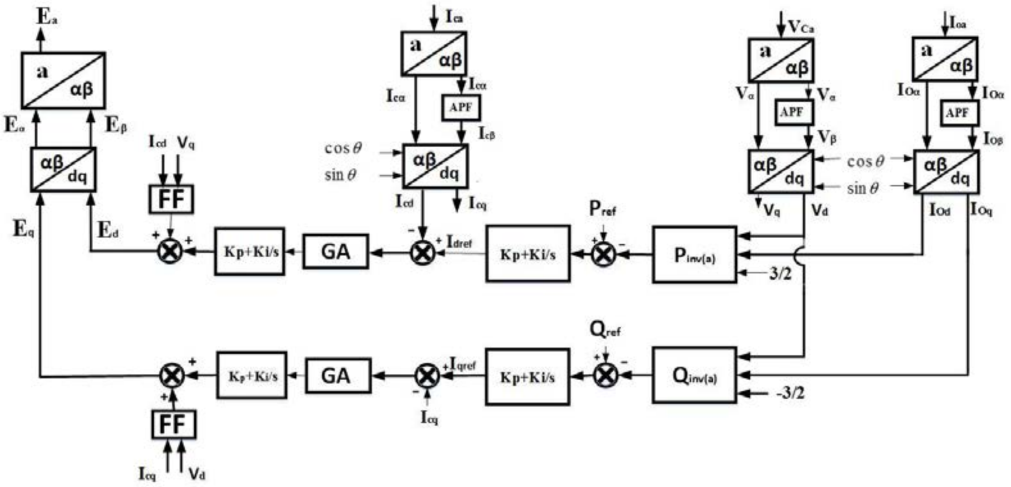

Fig. 5: The suggested power controller sterategy

3.1 Power control strategy

The balance between generation and consumption is an important component in the control of microgrids[9]. Moreover, an accurate power control between the utility grid and the microgrid in grid-tied mode must be achieved by a proper control scheme. Recently, PQ mode control has attracted more attention because the benefits it offers to the microgrids in grid-tied mode[11]. It should be noted that the DG units inject pre-specified active and reactive power to the microgrid using PQ control mode. In this study, the PQ control technique is used to generate the reference current vectors[17].

The main purpose of using power control strategy is to share the power requirements of loads among the DG units and the utility grid. As indicated in Fig. 5, the block diagram of the power controller is designed by the conventional PI-type controller. As seen in this figure, the external control loop is applied to ensure the reference signals (i_{dref} and i_{qref}). Note that, both P_{ref} and Q_{ref} are either set to pre-specified values or are commanded from the remote control.

In this paper, the PQ control technique on the basis of voltage oriented control is suggested for the three-phase four-leg inverter [14]. The control of active/reactive power is the main purpose of this controller, which must be achieved in grid-tied modes and during load changing conditions. In the PQ mode, a strong decoupling between control variable has been accomplished by a decoupling network. Moreover, the outputs of active and reactive power of VSI are regulated based on their reference pre-set or commanded values. Moreover, the conventional PI-type controllers make control parameters available to reference current vectors. Based on the PI controller in the dq frame the active and reactive power can be obtained as:

$$p = \frac{3}{2} v_d i_d. \tag{3}$$

$$Q = -\frac{3}{2} v_d i_q. \tag{4}$$

Also, the reference current vectors can obtained as:

$$i_{dref} = (P_{ref} - P_{inv})(K_{pp} + K_{ip}/s). \tag{5}$$

$$i_{qref} = (Q_{ref} - Q_{inv})(K_{pq} + K_{iq}/s). \tag{6}$$

3.2 Current control strategy

In this paper, a significant effort has been made in order to enhance the dynamic performance of current controller by applying an optimization technique. As illustrated in Fig. 5, the current controller comprises a controller based on the conventional PI-type regulator and GA block to optimize the current control parameters. The main aim of the current loop is to ensure short transient and appropriate signal tracking of the VSI output current. The left side in Fig. 5 illustrates the block diagram of the current controllers in the dq frame. Both PI controllers are employed to eliminate current error. In addition, the capacitor feed-back loop is used to enhance dynamic and steady-state performances.

4 Simulation results

To validate the operation of the suggested method the three-phase four-leg VSI is simulated in MATLAB/Simulink software. The parameters of the DG model used in this paper are defined as follows: $Ls = 3.5$ mH, $Rs = 1.15\ \Omega$, $f = 60$ Hz, filter capacitance $C = 15\ \mu f$, switching frequency for SPWM is fixed at 10 kHz and sampling frequency is fixed at 500 kHz. In this model, the suggested controller is presented on the basis of PQ method, and the GA is used to obtain optimum current control parameters. It is important to note that the obtained optimal values are $K_{vd} = K_{vd} = 10.411$ and $K_{id} = K_{id} = 7416$. In order to validate the performance of the suggested strategy, three simulation case studies are performed in the following subsections.

4.1 Load change during grid-tied mode

In this section, the grid-connected microgrid of Fig. 1 is considered as the test system to evaluate the effectiveness of the suggested controller. A load change has been considered to check the performance of the utility grid, when the power generation of the DG unit is more than the power requirement of the load. The initial values of active/reactive power of DG unit are set to 5kW real and 1kVar reactive power. Also, the load is set to 7kW active and 3kVar reactive power in initial operating point. At 0.6s, the load is gone up to 12kW active and 5kVar reactive power. It is desired that after 0.6s, the balanced power would be supplied by the utility grid.

Fig. 6 and Fig. 7 illustrate, respectively, the variation of active and reactive power of the utility grid during the load change condition, whereas the DG unit injects a constant output active and reactive power. Also, the frequency of the grid-connected microgrid during load change condition is shown in Fig. 8. As seen, the appropriate power flow is achieved through the proposed control strategy. Additionally, the frequency is controlled perfectly with the zero deviation. Before 0.6s, the utility grid injects 2kW active and 2kVar reactive power to the microgrid, but after 0.6s its active and reactive power are increased to 7kW and 2kVar As can be seen, the proposed control strategy has the ability to regulate the power exchange during the load change condition.

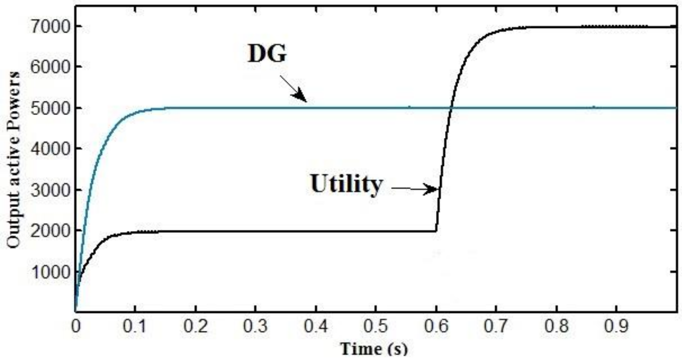

Fig. 6: Output active power of the microgrid at load change condition

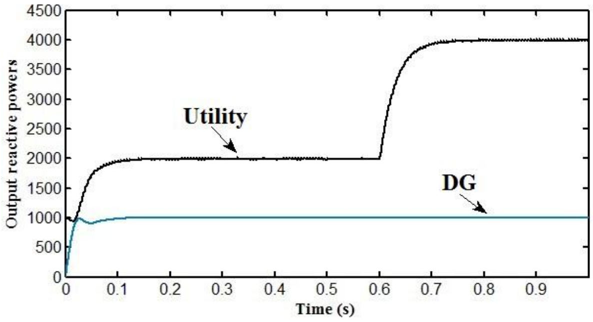

Fig. 7: Output reactive power of the microgrid at load change condition

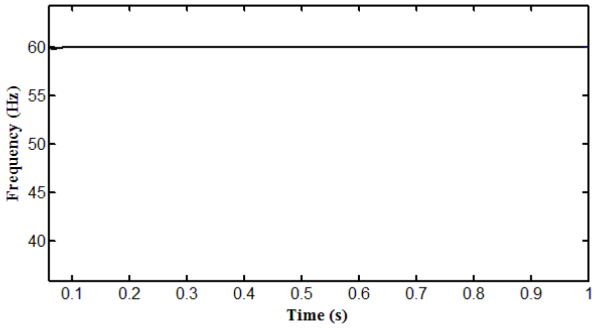

Fig. 8: Frequency of the microgrid

4.2 Set-point change of DG unit during grid-tied mode

In this stage, the behavior of the power control strategy is simulated during changes in active and reactive set points of DG unit. The load parameters are set to 7kW and 3kVar. Also, the 5kW active power and 2kVar reactive power are considered as an initial operating point for DG unit. At 0.6s, the initial values of the active and reactive power are changed to 3kW and 3kVar. As shown in Fig. 9, the active power of the DG unit is decreased to 3kW, thus the balanced power is supplied by the utility grid. In other words, the active power of utility grid is increased to 3kW. Fig. 10 shows the output reactive powers of the utility grid and the DG unit. It can be observed that the reactive power of DG unit is decreased to 3kVar, while the reactive power of the utility grid is increased to 2kVar. As seen, the suggested method provides the stable power flow between the microgrid and the utility grid. As can be seen, the proposed control strategy has the excellent capability to regulate the power exchange during the set-point change condition.

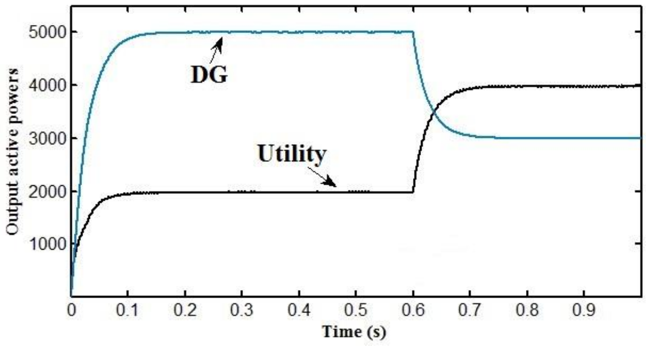

Fig. 9: The output active powers of the utility and the DG unit

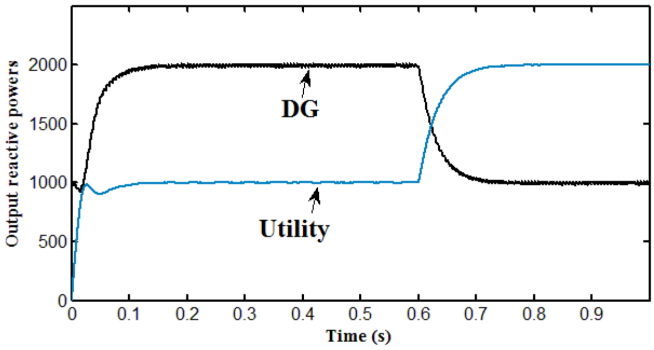

Fig. 10: The output reactive powers of the utility and the DG unit

5 Conclusion

This paper presents a novel control strategy for a three-phase four-leg VSI. The proposed control strategy consists of two cascaded loops, including an external power loop and an internal current loop. The outer power control regulates the power flow of the microgrid, while the inner current loop generates reference voltage signals for the PWM. Also, GA is used to ensure the stability of the current controllers. The effectiveness of the suggested control is demonstrated by using MATLAB/Simulink software environment. The simulation results conclude that the suggested strategy:

- Effectively controls the exchange of power flow between the microgrid and the utility grid during load change conditions,

- Robustly controls the injected active and reactive power of three-phase four-leg grid-connected VSI,
- Effectively controls the power flow of microgrid when the load power is lower or larger than the rated power of three-phase four-leg grid-connected VSI,
- Adequately optimize the current control parameters to ensure the system stability.

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