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Adaptive decoupled control of 4-leg voltage-source inverters for standalone photovoltaic systems: Adjusting transient state response

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ABSTRACT

Three leg inverters for photovoltaic systems have a lot of disadvantages, especially when the load is unbalanced. These disadvantages are for example, small utilization of the DC link voltage, the dependency of the modulation factor of the load current and the superposition of a DC component with the output AC voltage. A solution for these problems is the four-leg inverter. Consequently, generation of balanced voltage with sinusoidal waveform is necessary for these inverters. The power stage model of the 4-leg inverter in rotating coordinates *dqo* is highly coupled. Consequently, controller design procedure is very difficult and complex. On the other hand, adaptive control for 4-leg inverters has not yet been discussed in the literature. This paper proposes the state feedback approach to decouple the system and convert it to a second-order system which has two poles equal to zero. Then, it suggests a compensator to cancel poles of the closed-loop system and to convert the final system to a desired second-order system. Thanks to use of this strategy the transient performance of the system, such as overshoot and speed of response, becomes greatly adjustable. In addition, an STR (Self-Tuner Regulator) is introduced to tune the state feedback matrix and to guarantee the adaptive performance of the system. Simulation results validate that, by using proposed control strategy, the 4-leg inverter generates balanced voltage, with perfect sinusoidal waveform, in spite of the presence *RL* time-variant loads.

1. Introduction

The electrical energy gained from a photovoltaic (PV) system can be utilized in different ways. There are two kinds of the employment of solar modules, standalone and grid coupled systems. Standalone photovoltaic system [1–10] means that the system, composed of load and generator, is closed and locally limited. The energy supply of a ship or a space chattel is gained from a standalone network. Grid coupled system [10–20] means, that there is a supra-regional energy supply network and the generated energy, for example, from a PV system will be injected in this network. Both operation modes must satisfy different requirements on the energy supply. In the standalone system, the problem to solve is to ensure the energy supply. As the solar energy supply works only, if there is sun radiation, the gained energy must be stored.

Photovoltaic generators can only produce DC currents and therefore only DC loads can be supplied. To supply costumer AC loads an inverter unit must be applied. The inverter, which represents the interface between the photovoltaic generator and AC loads, is the main subject of this paper. Its task in context with standalone PV systems is to ensure the energy supply in three-phase standalone network.

The proposed standalone PV system is illustrated in Fig. 1. It consists of the PV generator, DC/DC1 converter, a battery energy storage, a second DC/DC2 converter, DC link capacitor bank, inverter, output filter and load. It can be seen that the proposed system is transformer less. For this reason a high DC link voltage is needed which is supplied with boost converter (DC/DC1). DC/DC2 is also a boost converter and acts as a maximum power point tracker (MPPT) and battery charger. In this way the battery will be always charged at the maximum power point.

The goal of the system illustrated in Fig. 1 is to supply three as well as single phase loads of any kind with constant amplitude sinusoidal voltage and constant frequency. To realize this, all three phases must be independent of each other. For this reason the neutral point of the LC output filter and load must be connected to a neutral point. There are a lot of possibilities to realize this. One possibility, which is the four-leg inverter, is shown in Fig. 2.

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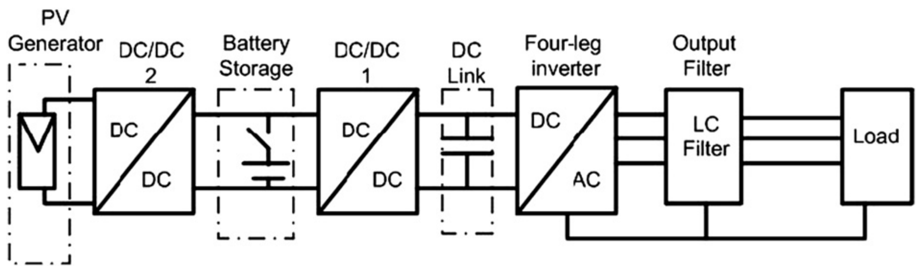

Fig. 1. Standalone photovoltaic system.

Because of additional neutral leg, 4-leg inverters are recommended for supplying unbalanced and/or nonlinear loads. Consequently, generation of balanced voltage, with sinusoidal waveform, is necessary for these inverters. As a result, using an appropriate load voltage controller is highly required.

To apply control techniques a DC operating point is needed. Thus, the transformation *T*, given in Appendix, is applied to the model of 4-leg inverter in *abc* coordinates to get the power stage model in rotating coordinates *dqo* [21,22].

The power stage is a highly coupled multi-variable multi-loop system, in rotating coordinates. Consequently, controller design for this model is very difficult. Most papers dealing with 4-leg inverters use classic controller, such as PI controller, for the system [22]. However, designing procedure becomes very complicated, because of presence of coupling in the power stage model. Moreover, the response in time domain does not become acceptable, in some cases. On the other hand Classic controllers are designed for one operating point while operating point changes along the time, because the load varies along the time in practice. This paper proposes the state feedback approach [23], which is a modern control technique [24], to decouple the model and to convert it to a second-order system with two poles, equal to zero. Then, it proposes a compensator to cancel the undesired poles and converts the closed-loop system to a desired second-order. In addition, an STR (Self-Tuner Regulator) [25] is introduced to guarantee the adaptive performance of the final system.

In fact this paper demonstrates that by using the proposed control strategy the 4-leg inverter produces balanced voltage in spite of the presence of RL time-variant loads. Additionally, the transient performance of the system becomes greatly adjustable.

After this introduction, large signal model of the inverter is represented in Section 2. Then, Section 3 describes state equations of the model. In Section 4, a decoupling control strategy is introduced. Also, a compensator which converts the closed-loop system to a desired second-order system is presented in this section. Section 5 defines an STR (Self-Tuner Regulator) to guarantee the adaptive performance of the system. Section 6 discusses about simulation results. Finally, in Section 7 some conclusions are pointed out. It should be noted that proposed control strategy can be used, similarly, for multilevel 4-leg inverters and other applications of the four-leg structure, such as active power filters and DVR (dynamic voltage resistor), but it is beyond the scope of this paper.

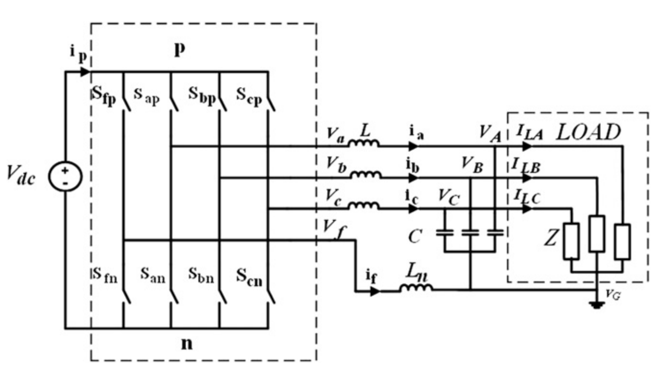

Fig. 2. Four-leg voltage-source inverter.

2. Four-leg inverters and their large signal model

Fig. 2 shows the power stage model of the three-phase 4-leg voltage-source inverter with second-order filter load. The average model in ABC stationary coordinates is shown in Fig. 3.

The output voltages and input current in the inverter can be represented as:

$$\begin{bmatrix} V_{af} & V_{bf} & V_{cf} \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} d_{af} & d_{bf} & d_{cf} \end{bmatrix}^{\mathrm{T}} \cdot V_{dc} \tag{1}$$

$$I_p = \begin{bmatrix} d_{af} & d_{bf} & d_{cf} \end{bmatrix} \cdot \begin{bmatrix} I_a & I_b & I_c \end{bmatrix}^{\mathrm{T}} \tag{2}$$

where (V_{af}, V_{bf}, V_{cf}) is the inverter output voltage (line-neutral), (I_a, I_b, I_c) is the line current and (d_{an}, d_{bn}, d_{cn}) is the line-to-neutral duty ratio.

The duty ratios, d_{an}, d_{bn} and d_{cn}, are controlled in a way so as to produce sinusoidal voltages at output of the filter, irrespective of the load. The system requirement can be expressed as:

$$\begin{bmatrix} V_{AG} \\ V_{BG} \\ V_{CG} \end{bmatrix} = V_m \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t - 120^\circ) \\ \cos(\omega t + 120^\circ) \end{bmatrix} \tag{3}$$

where (V_{AG}, V_{BG}, V_{CG}) is the load voltage and V_m is its amplitude.

To produce the desired sinusoidal output voltages, the steady state duty ratios have to be time-varying and sinusoidal in case of linear loads. But, to apply control techniques we need a DC operating point. Thus, we apply the transformation *T*, given in Appendix, to get the power stage model in rotating coordinates. Fig. 4 gives the power stage model in rotating coordinates with RL and it is redrawn as a Signal Flow Graph in Fig. 5. The *d* and *q* sub-circuits have coupled voltage and current sources.

The steady state output load voltages are DC quantities and are given as:

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} V_m \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

where V_m is the rated output voltage.