Control of Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters Based on Fuzzy Logic

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ABSTRACT

The penetration of photovoltaic (PV) solar power generation in distributed generation (DG) systems is growing rapidly. This condition imposes new requirements to the operation and management of the distribution grid, especially when high penetration levels are achieved. Under this scenario, the power electronics technology plays a vital role in ensuring an effective grid integration of the PV system, since it is subject to requirements related not only to the variable source itself but also to its effects on the stability and operation of the electric grid. This paper proposes an enhanced interface for the grid connection of PV solar systems. This paper addresses this issue and proposes a decoupled active and reactive power control strategy to enhance system operation performance. The relationship between output voltage components of each module and power generation is analyzed with the help of a newly derived vector diagram which illustrates the proposed power distribution principle. On top of this, an effective control system including active and reactive components extraction, voltage distribution and synthesization, is developed to achieve independent active and reactive power distribution and mitigate the aforementioned issue. Finally, a 3-MW, 12-kV PV system with the proposed control strategy is modelled and simulated in MATLAB. Simulation and experimental results are provided to demonstrate the effectiveness of the proposed control strategy for large-scale grid-connected cascaded PA full detailed model is described and its control scheme is designed. The dynamic performance of the designed architecture is verified by computer simulations and Further Extension can be done using Fuzzy Logic Controller.

Key Words: Photovoltaic, Fuzzy Logic Controller, Distributed Generation, Solar Power Generation, Large-Scale Grid-Connected Cascaded.

I. Introduction.

GLOBAL energy crises and environmental concerns [1]–[3] from conventional fossil fuels have attracted more and more renewable energy developments in the worldwide. Among of these renewable energy, solar energy is much easier to be harvested, converted, and delivered to grid by a variety of power converters [4]–[14]. In particular, large-scale grid-connected photovoltaic (PV) systems play a major role to achieve PV grid parity and have been put forward in high penetration renewable energy systems [15]. As one type of modular multilevel converters, cascaded multilevel converters share many merits of modular multilevel converters, e.g., lower electromagnetic interference,

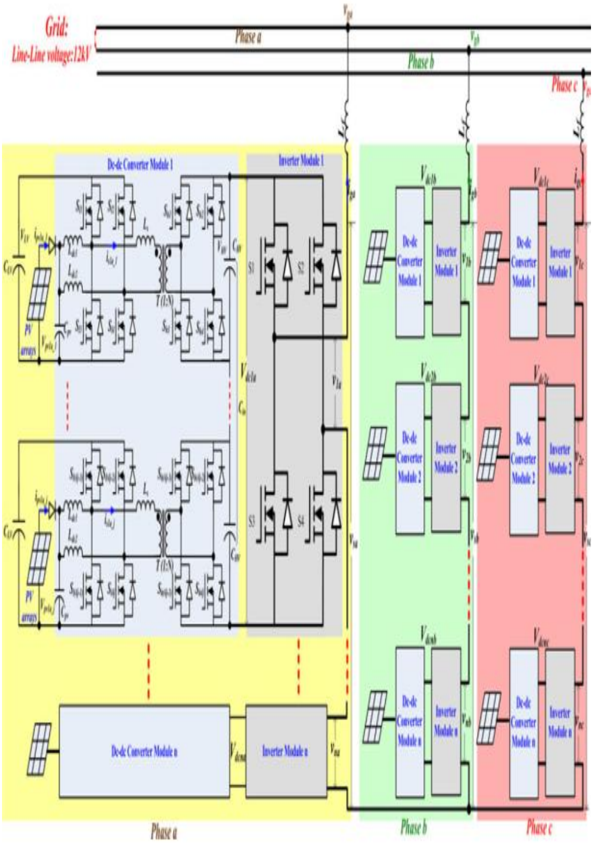


Fig 1: Proposed grid-connected PV system with cascaded multilevel converters at 3 MW.

low device rating, improved harmonic spectra, modularity, etc., but also is very promising for the large-scale PV system due to its unique advantages such as independent maximum power point tracking (MPPT) for segmented PV arrays, high ac voltage capability, etc. [11]–[14]. However, cascaded multilevel converters in PV systems are different from their some successful application such as medium voltage motor drive, static synchronous compensator (STATCOM), harmonic compensator, solid state transformer, which are connected with symmetrical segmented dc sources. PV systems with cascaded multilevel converters have to face tough challenges considering solar power variability and mismatch of maximum power point from each converter module due to manufacturing tolerances, partial shading, dirt, thermal gradients, etc. In a cascaded PV system, the total ac output voltage is synthesized by the output voltage from each converter module in one phase leg, which must fulfill grid codes or requirements. Because same grid current flows through ac side of each converter module, active power mismatch will result in unsymmetrical ac output voltage of these modules [14]. The converter module with higher active power generation will carry more portion of the whole ac output voltage, which may cause over modulation and degrade power quality if proper control system is not embedded into the cascaded PV system.

Several control strategies have been proposed for the cascaded PV system with direct connection between individual inverter module and segmented PV arrays. But they did not consider the fact that PV arrays cannot be directly connected to the individual inverter module in high-voltage large-scale PV system application due to the PV insulation and leakage current issues. Even if there are low-frequency medium-voltage transformers between the PV converters and grid, there are still complicated ground leakage current loops among the PV converter module. Therefore, those methods in are not qualified for a practical large-scale grid-connected cascaded PV system. Moreover, reactive power compensation was not achieved, which largely limits the functions of the cascaded PV system to provide ancillary services. Proper reactive power compensation can significantly improve the system reliability, and in the meantime help the MPPT implementation for the cascaded module under unsymmetrical condition aswell as comply with the system voltage requirement simultaneously. A reactive and active power control strategy has been applied in cascaded PV system with isolated dc–dc converter. If symmetrical active power comes from each module, active and reactive power can be equally distributed into these modules under traditional power control. However, if unsymmetrical active power is generated from these modules, this control strategy will not be able to achieve decoupled active and reactive power control. Reactive power change is along with the active power change at the same direction, which may aggravate output voltage overmodulation during unsymmetrical active power outputs from segmented PV arrays. In order to solve the aforementioned issues, this paper proposes a large-scale grid-connected cascaded PV system including current-fed dual-active-bridge (CF-DAB) dc–dc converters and cascaded multilevel inverters as shown in Fig. 1. A decouple active and reactive power control system is developed to improve the system operation performance. Reactive power from each PV converter module is synchronously controlled to reduce the over modulation of PV converter output voltage caused by unsymmetrical active power from PV arrays. In particular, the proposed PV system allows a large low-frequency dc voltage ripple for each PV converter module, which will not affect MPPT achieved by CF-DAB dc–dc converters. As a result, film capacitors can be applied to replace the conventional electrolytic capacitors, thereby enhancing system lifetime.

II. Basics Components

IGBTS

The insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch which, as it was developed, came to combine high efficiency and fast switching. It switches electric power in many modern appliances: variable-frequency drives (VFDs), electric cars, trains, variable speed refrigerators, lamp ballasts, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to turn on and off rapidly, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters. In switching applications modern devices feature pulse repetition rates well into the ultrasonic range—frequencies which are at least ten times the highest audio frequency handled by the device when used as an analog audio amplifier.

The Insulated Gate Bipolar Transistor also called an IGBT for short, is something of a cross between a conventional Bipolar Junction Transistor, (BJT) and a Field Effect Transistor, (MOSFET) making it ideal as a semiconductor switching device. The IGBT transistor takes the best parts of these two types of transistors, the high input impedance and high switching speeds of a MOSFET with the low saturation voltage of a bipolar transistor, and combines them together to produce another type of transistor switching device that is capable of handling large collector-emitter currents with virtually zero gate current drive.

Fig 2: Typical IGBT

The Insulated Gate Bipolar Transistor, (IGBT) uses the insulated gate (hence the first part of its name) technology of the MOSFET with the output performance characteristics of a conventional bipolar transistor, (hence the second part of its name). The result of this hybrid combination is that the "IGBT Transistor" has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET.

IGBTs are mainly used in power electronics applications, such as inverters, converters and power supplies, were the demands of the solid state switching device are not fully met by power bipolars and power MOSFETs. High-current and high-voltage bipolars are available, but their switching speeds are slow, while power MOSFETs may have higher switching speeds, but high-voltage and high-current devices are expensive and hard to achieve.

The advantage gained by the insulated gate bipolar transistor device over a BJT or MOSFET is that it offers greater power gain than the standard bipolar type transistor combined with the higher voltage operation and lower input losses of the MOSFET.

The **Insulated Gate Bipolar Transistor** can be used in small signal amplifier circuits in much the same way as the BJT or MOSFET type transistors. But as the IGBT combines the low conduction loss of a BJT with the high switching speed of a power MOSFET an optimal solid state switch exists which is ideal for use in power electronics applications.

Also, the IGBT has a much lower "on-state" resistance, R_{ON} than an equivalent MOSFET. This means that the I^2R drop across the bipolar output structure for a given switching current is much lower. The forward blocking operation of the IGBT transistor is identical to a power MOSFET.

When used as static controlled switch, the insulated gate bipolar transistor has voltage and current ratings similar to that of the bipolar transistor. However, the presence of an isolated gate in an IGBT makes it a lot simpler to drive than the BJT as much less drive power is needed.

IGBT Comparison Table

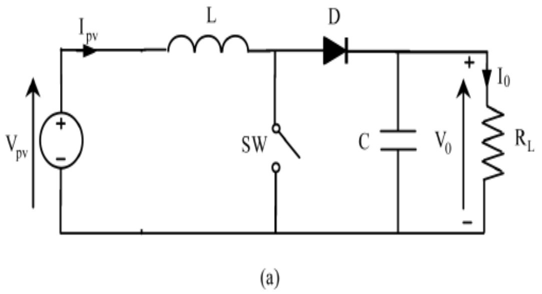
Device Characteristic	Power Bipolar	Power MOSFET	IGBT
Voltage Rating	High <1kV	High <1kV	Very High >1kV
Current Rating	High <500A	Low <200A	High >500A
Input Drive	Current 20-200 h_{FE}	Voltage V_{GS} 3-10V	Voltage V_{GE} 4-8V
Input Impedance	Low	High	High
Output Impedance	Low	Medium	Low
Switching Speed	Slow (uS)	Fast (nS)	Medium
Cost	Low	Medium	High

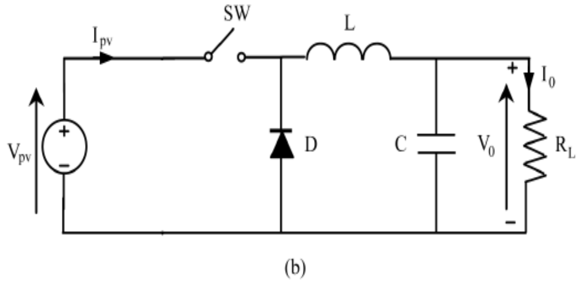
b). DC-DC Converter

There are several ways of incorporating transformer isolation into any dc-dc converter. The fullbridge, half-bridge, forward, and push-pull converters are commonly used isolated versions of the buck converter. Similar isolated variants of the boost converter are known. The flyback converter is an isolated version of the buck-boost converter. Isolated variants of the SEPIC and Cuk converter are also known. The full-bridge, forward, and fly back converters are briefly described in this section.

The three basic DC-DC converters commonly used in PV systems are: buck, boost and buck-boost converters, are shown in Fig 3. The characteristic parameters of each topology can be described by the following para- meters listed in Table 2. The converter can operate in two distinct modes of operation, the continuous conduction operation (CCO) or the discontinuous conduction operation (DCO). The CCO occurs when inductance current is always greater than zero and is preferred for high efficiency and good utilization of semiconductors switches and passive components. The DCO is not preferred since the dynamic order of the converter is reduced.

The inductance L is used to filter the input and output current of the converter. Lbo is the boundary value of L for a given duty cycle α to ensure that the chopper is operated in CCO mode. The capacitance C allows minimizing the output voltage ripple of the converter, so Cbo is the boundary capacitance value required for a given duty cycle α to reduce the output ripple voltage of the converter to specified desired value. The above parameters can be computed using the relationships given in Table 2. We note that these relations were deduced under the assumption that the converter is lossless and always operates in CCO mode.





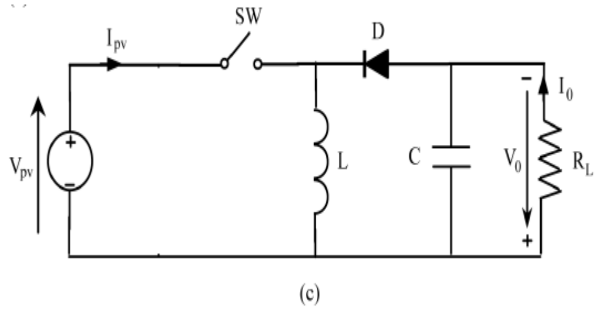


Figure 3. DC-DC converters diagram commonly used. (a) Boost; (b) Buck; (c) Buck-boost.

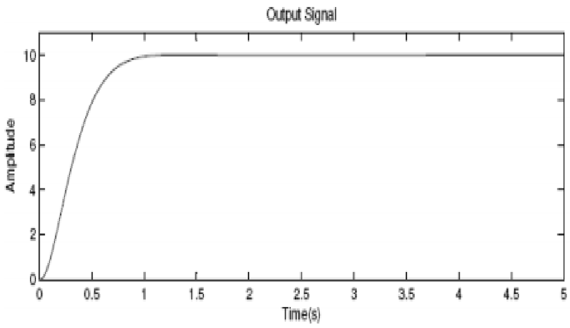
Parameter	boost	buck	buck- boost
$A_v = \frac{V_0}{V_{pv}}$	$\frac{1}{1-\alpha}$	α	$\frac{\alpha}{1-\alpha}$
$A_i = \frac{I_0}{I_{pv}}$	$1-\alpha$	$\frac{1}{\alpha}$	$\frac{1-\alpha}{\alpha}$
R_{in}	$(1-\alpha)^2 R_L$	$\frac{R_L}{\alpha^2}$	$\frac{(1-\alpha)^2}{\alpha^2} R_L$
L_{bo}	$\frac{(1-\alpha)^2 \alpha R_L}{2f}$	$\frac{(1-\alpha) R_L}{2f}$	$\frac{(1-\alpha)^2 R_L}{2f}$
C_{bo}	$\frac{\alpha V_0}{\Delta V_0 R_L f}$	$\frac{(1-\alpha) V_0}{8 \Delta V_0 L f^2}$	$\frac{\alpha V_0}{\Delta V_0 R_L f}$

Table 2. Characteristic parameters for each DC-DC converter.

III. Proposed Technique

Fuzzy logic controller

A fuzzy logic controller has four main components as shown in Figure 5: fuzzification interface, inference mechanism, rule base and defuzzification interface. FLCs are complex, nonlinear controllers. Therefore it’s difficult to predict how the rise time, settling time or steady state error is affected when controller parameters or control rules are changed. On the contrary, PID controllers are simple, linear controllers which consist of linear combinations of three signals.



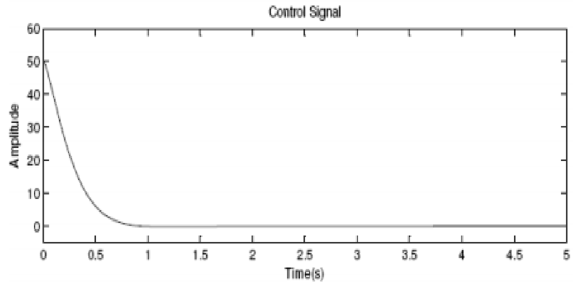


Figure 4. Output and control signals for crisp PD control system

Implementation of an FLC requires the choice of four key factors: number of fuzzy sets that constitute linguistic variables, mapping of the measurements onto the support sets, control protocol that determines the controller behaviour and shape of membership functions. Thus, FLCs can be tuned not just by adjusting controller parameters but also by changing control rules, membership functions etc. The main advantages of adaptive fuzzy control over non adaptive fuzzy control are: better performance is usually achieved because the adaptive fuzzy controller can adjust itself to the changing environment, and less information about the plant is required because the adaptation law can help to learn the dynamics of the plant during real time operation. However, these approaches still have some problems. The adaptive control scheme proposed by Wang [13] guarantees the uniform bounded ness of all signals of the control system but it is applicable only to single-input single-output system. In many applications, the structure of the model of the plant may be known, but its parameters may be unknown and/or change with time. Recently, the concept of incorporating fuzzy logic control into the model reference adaptive control has grown into an interesting research topic.

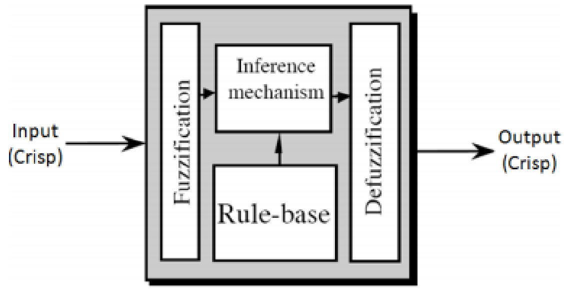


Fig 5: Fuzzy Logic Controller.

Moreover, it can eliminate multiple harmonics in the circulating current with a single repetitive controller. However, the repetitive controller and the FUZZY controller are paralleled. Such an arrangement imposes unnecessary limitation on the FUZZY controller design and also complicates the repetitive controller design. This paper proposes a different repetitive-plus-FUZZY control scheme. The improved plug-in configuration of the repetitive controller avoids the above problems while keeping all the advantageous features.

In some control tasks, such as those in robot manipulation, the systems to be controlled have constant or slowly-time varying uncertain parameters. Unless such parameter uncertainty is gradually reduced on-line by an appropriate adaptation or estimation mechanism, it may cause inaccuracy or instability for the control systems. In many other tasks, such as those in power systems, the system dynamics may have well known dynamics at the beginning, but experience unpredictable parameter variations as the control operation goes on. Without continuous redesign of the controller, the initially appropriate controller design may not be able to control the changing plant well. The problem of adaptation of dynamical systems having parameter uncertainty has attracted a lot of research efforts in all times. In particular, for nonlinear systems, several approaches have been proposed to deal with this important problem [5-7]. On the other hands, as a model free design method, fuzzy logic systems have been successfully applied to control complex or mathematically poorly understandable systems. However, the fuzzy control has not been regarded as a rigorous science due to the lack of guaranteed global stability and acceptable performance. To overcome these drawbacks, during the last decade, there has been growing interest in systematic analysis and design of fuzzy control systems such as stability and robustness [8-12]. In recent years, in order to deal with the uncertainties of nonlinear systems in the fuzzy control system literature, a lot of effort has been put to adaptive fuzzy control system such as neural network based approaches, and the TS model based approaches.

Rule base, inference mechanism and defuzzification methods are the sources of nonlinearities in FLCs. But it's possible to construct a rule base with linear input-output characteristics. For an FLC to become a linear controller with a control signal U = E + CE. Where E is "error" and CE is "change of error", some conditions must be satisfied :

1. Support sets of input linguistic variables must be large enough so that input values stay in limits.
2. Linguistic values must consist of symmetric triangular fuzzy sets that intercept with neighbouring sets at a membership value of so that for any time instant, membership values add to 1.
3. Rule base must consist of -combinations of all fuzzy sets.
4. Output linguistic variables must consist of singleton fuzzy sets positioned at the sum of the peak positions of input fuzzy sets.
5. Should be multiplication and defuzzification method must be "centre of gravity" (COGS).

IV. RESULT

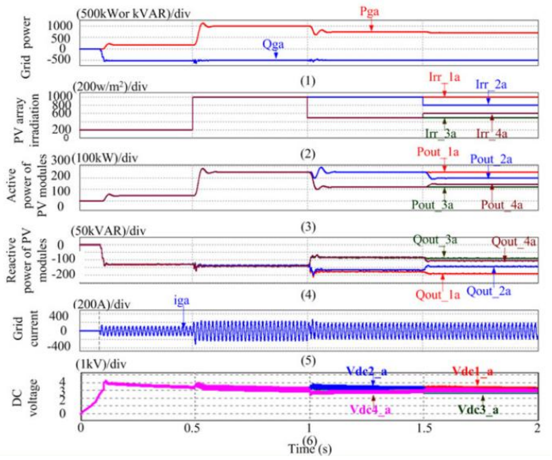


Fig. 6. Simulation results of PV system with traditional active and reactive power control in phase a (Power distribution.)

V. CONCLUSION

This paper addressed the active and reactive power distribution among cascaded PV inverter modules and their impacts on power quality and system stability for the large-scale grid connected cascaded PV system. The output voltage for each module was separated based on grid current synchronization to achieve independent active and reactive power distribution. A decoupled active and reactive power control strategy was developed to enhance system operation performance. Here in this paper we had proposed Fuzzy Logic Based Control of Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters where the controlling circuit or the controller is fuzzy which gives a better results when compared to the previous PI controller. This particular concept of fuzzy controller provides an remarkable reduce of THD values of the previous circuit which is employed by PI controller.

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