Fuzzy Based Minimization of the DC Component in Transformerless Three-Phase Grid-Connected Photovoltaic Inverters

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Abstract: The dc component can produce line-frequency power ripple, dc-link voltage ripple, and a further second-order harmonics in an ac current. This project has proposed a better solution to reduce the dc component in three-phase ac currents and developed a logical-based approach to mimic the blocking capacitors which used for the dc component minimization, the so-called virtual capacitor. The virtual capacitor concept has been achieved by adding an integral of the dc component in the current feedback path. A method for getting an accurate extrication of the dc component based on double time integral, has been devised and approved effective even under the grid-frequency variation and harmonic conditions.

1. Introduction

Initially transformers (50/60Hz) give galvanic isolation between PV input and grid side for safety purpose [1]. But creates the system bulky, heavy and expensive and power loss also, these factors decrease the overall efficiency of the system. So transformerless power conversion method is implemented for the above reason [1-5]. Galvanic connection of the grid and dc sources in transformerless systems can produce additional ground currents due to the ground parasitic capacitance [6]. By using these techniques, the dc component can be affecting the normal system operation and cause safety concerns. The dc component can have some negative impacts on the power system in the below ways:

1) The dc component can affect the operating tip of the transformers in the power system. The service life time of the transformer is reduced as a result with further improved hysteresis and vortex current losses and noises.

2) The dc component can circulate between the inverter phase legs as well as among inverters in a resembled configuration. The dc component revolution affects the even current and loss distribution among paralleled inverters.

3) The dc component fed to the grid can collapse the normal operation of the loads connected to the grid, for example, causing torque ripples and extra losses in ac motors.

4) The corrosion of grounding wire in substations is increased due to the dc component.

Reduction of the dc component from transformerless PV inverters has been extensively looked up in literatures. It is also possible to use a DC blocking capacitor across the inverter output. A more recent method is to use the current sensing and control techniques for monitoring and calibrating the DC link current sensors [7]. In this concept, Special inverter typologies such as two-level or three-level half-bridge configurations are not extendable to other inverter topologies.

The auto-calibrating techniques for dc-link sensors in 2-level and 3-level single-phase inverters were proposed, which are effective to minimize the dc component caused by sampling biases of the ac current sensors [8]. However, these methods are not suitable for the dc component caused by other sources, e.g. asymmetry in switching behavior and an extra dc-link current sensor is required. The dc component minimization methods of single-phase PV inverters differ from that of three-phase PV inverters. In three-phase PV inverters, dc component may exist in each phase and flow between phases. It’s more challenging to minimize the dc component for all the three phases at the same time due to their couplings.

Among the above solutions, ‘virtual capacitor’ concept was proposed in [8] to minimize the dc component in single-phase PV inverters. It restores the physical capacitor which could block the dc component on the ac side with a novel control strategy. Generally, this capacitor should be large enough to avoid exceeding losses of the grid-connected inverter system.

A Fuzzy logic control based resonant controller is trained to generate maximum power corresponding
to the given solar panel irradiance level and temperature. The control logic has been 
implemented by using set of rules. The response of the FIS-based control system is mostly precise and 
offers an extremely fast response. The simulation results show various control operations of the 
system, and power flow management between the PV source, charging station and the grid works as 
shown in Fig.1. The simulation of this proposed and existing system has been designed in Matlab / 
Simulink. The hardware implementation and study on system efficiency as well as power quality at the 
grid-connection point are currently in progress.

2. Three - Phase Transformerless PV 
Inverter System

A new essential method based on the sliding window iteration algorithm and double time 
integral is proposed in this paper. This method is effective for reducing the DC component. The 
extraction of the dc component even for currents with frequency fluctuations and harmonics are 
reduced. A Fuzzy Resonant controller is used with virtual capacitor to reduce the dc component and frequency. A Fuzzy Logic controller is per phase control and Fuzzy - R controller is used for overall 
control. AC side LCL filter is used for dc component filtering.

Figure 1. Block Diagram of Proposed System

The PV array is connected to the grid via a three-phase voltage-source two-level inverter and an LCL 
filter. The capacitors of the LCL filter can be configured with a delta or star connection. In this 
paper, a delta connection is used to reduce the required capacitor and cost as opposed to the star 
connection, which has the benefit of smaller short-circuit current. The dual closed-loop control 
strategy, is a relatively common control strategy in three-phase PV inverters is shown in Fig.2.

In order to analyze the impact of dc components on the three-phase PV systems, the dc components 
have been added in the system model in addition to the line (fundamental) -frequency components. If 
other harmonics are neglected and only the dc and line-frequency components are concerned, F can be 
defined as an electrical variable (e.g. for ac-side voltage and current) and is expressed as in (1) in 
each coordinate (three-phase stationary (a-b-c), two-phase stationary (α-β), and two-phase rotational (d-q)).

\[
\begin{align*}
F_a &= F_{a0} + F_{a1} \\
F_b &= F_{b0} + F_{b1} \\
F_c &= F_{c0} + F_{c1}
\end{align*}
\]

where, the subscript 0 denotes the dc component and the subscript 1 denotes the line-frequency 
component. In a three-phase three-wire system, there is no current flowing through the neutral 
point and hence,

\[
\begin{align*}
F_{a0} + F_{b0} + F_{c0} &= 0 \\
F_{a1} + F_{b1} + F_{c1} &= 0
\end{align*}
\]

The coordinate transformations of the dc components from a-b-c coordinate to α-β and d-q 
coordinate can be expressed as,

\[
\begin{align*}
F_{a0} = \frac{1}{3} F_{0} \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & -\cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_{a0} \\ F_{b0} \\ F_{c0} \end{bmatrix} \\
F_{a1} = \frac{1}{\sqrt{3}} F_{d} \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ -1 & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} F_{a0} \\ F_{b0} \\ F_{c0} \end{bmatrix} \\
F_{b0} = \frac{1}{\sqrt{6}} F_{d} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ -1 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} F_{a0} \\ F_{b0} \\ F_{c0} \end{bmatrix}
\end{align*}
\]
where, $\theta$ is the angle between the $d-q$ coordinate and $a-b-c$ coordinate. By the coordinate transformation, $F_{a0}$, $F_{b0}$ and $F_{c0}$ (dc components) in the stationary $a-b-c$ frame can be transformed into $F_\alpha$ and $F_\beta$ in the stationary $\alpha-\beta$ frame and then $F_d$ and $F_q$ (line-frequency) in $d-q$ frame. Therefore, the voltage and current in the control loop of each frame will contain both dc and line-frequency components.

The synthesized vector $F$ of dc components can be decomposed in the frames, where $F$ is a stationary vector. Since the $d-q$ frame rotates anticlockwise, the dc component in the synchronous $d-q$ frame appears in the form of a negative-sequence line-frequency component as shown in Fig.

**Figure 3. Coordinate Transformation of DC Components**

### 3. Minimization of DC Component in Three Phase System

#### 3.1. Virtual Capacitor

There is a way to block the dc component is to put a capacitor (C) in series with the ac side of the inverter. However, in order to reduce the capacitive opposition flow at other frequencies, the capacitor value needs to be high, which increases the size and cost of the system. This type of series capacitor may also be affect the system dynamic response and reduce transmission efficiency. In spite of, the physical capacitor can be restored by software-based method and advanced control strategy which take off the operation of the series capacitor in a single-phase PV system is shown in Fig.4.

where, $V_o$, $I_o$ is the inverter output voltage and current; $e_g$ is the gird voltage; $V_o(s)$, $I_o(s)$ and $e_g(s)$ are the Laplace transforms of $V_o$, $I_o$ and $e_g$ in the frequency domain, respectively; $L$ is the filter inductance; $R$ is the line equivalent resistance; $C$ is the blocking capacitor.

Substituting the operator $s$ with $j\omega$, $I_o(j\omega)$ equals zero when $\omega=0$ (dc). This indicates that the blocking capacitor can minimize the dc component effectively.

**Figure 4. A Single-Phase Grid-Connected PV Inverter with The Blocking Capacitor**

The current control loop diagram of the single-phase PV inverter with the blocking capacitor is shown in Fig. 5, where $i_o^*$ is the reference current; $G(s)$ is the controller transfer function and $K_{PWM}$ is the gain of pulse width modulator.

**Figure 5. Current Control Loop Diagram**

When the capacitor voltage feedback terminal $(1/Cs)$ is moved to the front of the pulse width modulator (KPWM), the control system can be equivalently transformed to the structure shown in Fig. 6. As seen, the blocking capacitor C in Fig. 5 is replaced with an integral and feedback block, the so-called ‘virtual capacitor’.

**Figure 6. Equivalent Transformation of The Current Control Loop With Virtual Capacitor Concept**

This virtual capacitor can be developed with software-based method and avoids the uses of
physically big and expensive ac capacitors to block the dc component.

3.2. DC Component Extraction Based on Sliding Window Iteration

In the control strategy shown in Fig. 9, an accurate dc component measurement and extraction is the key to implement the virtual capacitor concept and achieve the overall dc component minimization.

In PV inverters, the Hall-effect current sensors are widely used to measure the ac-side currents (including both ac and dc components) due to their smaller size, isolated output and wide bandwidth (e.g. from dc to several hundred kHz). In this paper, an integral method based on the sliding window iteration algorithm is used to accurately extract the dc component from the ac-side currents.

3.3. Fuzzy Logic Control System

A fuzzy logic control system is a control system based on fuzzy logic- a mathematical system which analyzes the analog input signals in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic system, which operates on discrete values of either 0 or 1 (true or false, respectively). Fuzzy logic is widely used in a machine control applications. The term "fuzzy" mentions to the fact that the logic involved with which concepts that cannot be expressed as the "true" or "false" but rather as "partially true".

3.4. Photovoltaic System

In general, PV modules can generate DC current and voltage. However, to inject the electricity to the grid, AC current and voltage only needed. Inverters are the equipment used to change DC to AC. In addition, they can be in charge of keeping the operating tip of the PV array at the MPP. This is usually done with computational MPPT tracking algorithms. There are different inverter configurations depending upon how the PV modules are connected to the inverter. If the modules are not alike or do not work under the same conditions, the MPPT is different in each panel and the resulting voltage-power characteristics have analysed because most MPPT algorithms link-up to a local maximum depending upon the starting point. If the operating point is not the MPP, not all the possible power is being fed to the grid. For those reasons each case has to be carefully measured to optimize the plant and obtain the maximum performance.

3.5. Maximum Power Point Tracking Algorithms

The MPPT algorithms are necessary in renewable energy applications because the MPP of a solar panel changes with the irradiation and temperature, so the need of MPPT algorithms is required in order to obtain the maximum power from a solar array. There are 19 different MPPT algorithms can be found. Among the above techniques, the P&O and the InCond algorithms are the most common.

4. Simulation Results

Simulation has become a very popular tool on the industry application as well as in academics, now days. It is one of the best ways to develop the
system or circuit behavior without damaging. The tools for doing simulation in various fields are accessible in the market for engineering professionals. Many industries are spending a considerable part of time and money for doing simulation before manufacturing their products. In most of the research and development (R&D) related work, the simulation plays a very powerful role. Without simulation it is quite not possible to proceed further. It should be noted in power electronics, computer simulation and a proof of concept for hardware prototype in the laboratory are compatible to each other. However computer simulation must not be examined as a replacement for hardware prototype.

The PV array is composed of serial-parallel-connected PV panels (every panel in series then paralleled). The transient response of the dc components is evaluated when the proposed dc component minimization control is applied. As seen, the dc components have been successfully attenuated with the proposed strategy after the control is applied. To validate and analyze the quality of output with and without DC component feed forward controller by simulations were performed in MATLAB/Simulink. With the PIR controller, this error can be effectively attenuated with the resonant controller. Therefore, the d-axis and q-axis currents can track the reference well and the dc current is minimized. The objective of this chapter to describe simulation of impedance source inverter with R, R-L, and RLE loads using MATLAB tool.

4.1. PIR Simulation Results

![Figure 8. Full Circuit of Transformerless Inverter With PIR Control](image)

![Figure 9. PV Panel Output for PIR Control](image)

![Figure 10. DC-Link Voltage](image)

![Figure 11. Inverter Voltage and Current](image)

The parameters of the PI controller should be set to guarantee a good dynamic and steady-state performance of the current loop. The parameters of the R controller are set for the dc component minimization. The new control structure is based on the dc component feed-forward in the feedback path of the inverter-side current and PIR controllers for dc component minimization. The dc component of the ac-side currents will appear in the inner current control loop (e.g. \(i_d\), \(i_q\)) into the form of a negative-sequence line-frequency current.

So, the R controller and PI controller are combined into form a PIR controller to provide a better control for both the dc and line-frequency (negative sequence) signals of the current loop.
Figure 12. Grid Voltage and Current with PIR Control

Figure 13. THD for PIR Controller

The total harmonic distortion present in the PIR controller is 0.53%. But the THD should be less than 0.5 then only the overall system is acceptable to the IEEE standard. In order to reduce the THD level below 0.5 we are going for the Fuzzy logic controllers.

4.2. Fuzzy-R Simulation Results

Figure 14. Full Circuit of Transformer Less Inverter with Fuzzy-R Control

Fuzzy works on Rule-based operation (any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated. This makes the rule base complex so it is better to break the system into smaller chunks using several FL controllers)

Figure 15. PV Panel Output Voltage and Current for Fuzzy-R Controller

Figure 16. Inverter Voltage and Current with Fuzzy-R Controller

Figure 17. Grid Voltage and Current for Fuzzy-R Controller

Figure 18. DC-Link Voltage for Fuzzy-R Controller
For the same level of input voltage and input current THD level in the fuzzy controller is less than the THD in the PI controller and the output voltage is also increased compared to PI controller. This is observed from the FFT analysis shown above. So it is concluded that Fuzzy is more efficient than PI.

5. Conclusion

This paper has presented an effective solution to minimize the dc component in a three phase transformer less grid-integration PV system. The dc component can developed line-frequency power ripple in the system and further generate dc-link voltage ripple and 2nd order harmonics in the ac currents.

A PIR controller has been designed to activate the precise regulation of both the dc and line-frequency component in the d-q frame. Experimental results have verified the proposed method, where the dc component has been minimized below 0.5% and the dc-link voltage ripple has been reduced as well. The proposed method can be well adopted in the existing PV systems for dc component minimization by adding software programs for dc-component extraction, dc-component feed-forward term as well as the resonant controller in the current control loops.

6. Future Scope

An adaptive Fuzzy Logic control is used to minimize the DC component. The adaptive fuzzy system tunes its rules as it samples new data. So, the total DC component Minimization time is much more reduced. Therefore, the system total cost also reduced.

7. References


