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EFFECTIVE SOLUTION TO MINIMIZE THE DC COMPONENT IN THREE-PHASE AC CURRENTS

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Abstract—This paper presents a novel system with improving the photovoltaic (PV) inverter systems and may cause problems regarding system operation and safety. IEEE standard 1547-2003 has defined the limit for dc component in the grid-side ac currents, e.g., below 0.5% of the rated current. The dc component can cause line-frequency power ripple, dc-link voltage ripple, and a further second-order harmonic in the ac current. This project has proposed an effective solution to minimize the dc component in three-phase ac currents and developed a software-based approach to mimic the blocking capacitors used for the dc component minimization, the so-called virtual capacitor. The "virtual capacitor" is achieved by adding an integral of the dc component in the current feedback path. A method for accurate extraction of the dc component based on double time integral, as a key to achieve the control, has been devised and approved effective even under grid-frequency variation and harmonic conditions. A proportional integral- resonant controller is further designed to regulate the dc and line-frequency component in the current loop to provide precise control of the dc current. The proposed method has been validated in MATLAB software, where the dc current has been effectively attenuated to be within 0.5% of the rated current. The total harmonic distortion and the second-order harmonic have also been reduced as well as the dc-link voltage ripple.

INTRODUCTION

distributed generators (DGs), are primed to play a central role in future distribution systems. If properly integrated, DGs present two main advantages. First, they increase the efficiency of the system by avoiding transmitting power over long distances. Second, emissions are reduced.since most DGs are based on renewable like wind and solar. Their integration into distribution systems is thus one of the main challenges the power industry will be facing in the coming years. Up to now, interconnection standards for DGs have been mostly defensive, focusing on safe operation. For instance, IEEE-1547 states DGs should disconnect as quickly as possible under abnormal conditions.However, the recognition that their aggregated behavior may have an impact on the bulk power system is paving the path for new transmission-type regulations. As the installed power of DGs grows, grid codes are being modified to consider provision of ancillary services such as: controlled active power output, steady-state voltage regulation, and fault ride-through (FRT) capabilities. The latter may require DGs not only to remain connected in the event of a fault, but also to support the grid through the injection of reactive power. In the German MV grid code introduced in 2008 [4], this requirement is already included under the rubric of "dynamic grid support." Photovoltaic (PV) power generation represents a key technology for realizing the DG concept. As the cost of PV panel production continues to decrease, it is expected that solar power generation will be competitive with other

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forms of renewable energy, and hence massively deployed. PV systems are connected to the ac grid via a power electronic interface. This interface may include a boost dc/dc converter, and an inverter.The two-level voltage-source inverter (VSI) is widely adopted as the configuration of choice by most major PV system manufacturers. When the boost converter is eliminated by connecting an appropriate number of PV panels in series, the resulting architecture is referred to as single-stage topology. This architecture is more efficient and economical than its two-stage counterpart under homogeneous irradiance conditionsand is the subject of this paper. this paper proposes a novel FRT control scheme for PV inverters able to perform "dynamic grid support" through the injection of reactive power under unbalanced grid faults. The control scheme enables adjustable power quality as a tradeoff between power ripple and current harmonics, and therefore can be adapted to comply with different operational standards. The inverter is operated under current control mode, and the controller is implemented in the α–β stationary frame based on the SVFT concept. No rotational transformation is required, and zero steady-state error is ensured for the positive sequence harmonic components selected to be controlled.

DC- AC CONVERTER (INVERTER)

There are two main types of inverter. The output of a modified sine wave inverter is similar to a square wave output except that the output goes to zero volts for a time before switching positive or negative. It is simple and low cost (~$0.10USD/Watt) and is compatible with most electronic devices, except for sensitive or specialized equipment, for example certain laser printers. A pure sine wave inverter produces a nearly perfect sine wave output (<3% total harmonic distortion) that is essentially the same as utility-supplied grid power. Thus it is compatible with all AC electronic devices. This is the type used in grid-tie inverters. Its design is more complex, and costs 5 or 10 times more per unit power (~$0.50 to $1.00USD/Watt).[1] The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converters was made to work in reverse, and thus was "inverted", to convert DC to AC. The inverter performs the opposite function of a rectifier.

OVERVIEW OF PHOTOVOLTAICS

The conversion of solar radiation occurs by the photovoltaic effect which was first observed by Becquerel. It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Energy conversion devices which are used to convert sunlight to electricity by the use of the photo-voltaic effect are called solar cells. Single converter cell is called a solar cell or more generally photovoltaic cell and combination of such cells designed to increase the electric power output is called a solar module or solar array and hence the name 'Photovoltaic Arrays'. Solar cells can be arranged into large groupings called arrays. These arrays, composed of many thousands of individual cells, can function as central electric power stations, converting sunlight into electrical energy for distribution to industrial, commercial and residential users. Solar cells in much smaller configurations are commonly referred to as solar cell panels or simply panels. Practically, all photovoltaic devices incorporate a P-N junction in a semiconductor across which the photo voltage is developed. The solar panels consist mainly of semiconductor material, with Silicon being most commonly used.

Solar Cell Characteristics

The current-to-voltage characteristic, power-to-voltage characteristics of a solar cell are non-linear, which make it difficult to determine the maximum power point. It is straightforward to determine the maximum power point on a linear curve as maximum power is transferred at the midpoint of the current-voltage characteristic. A

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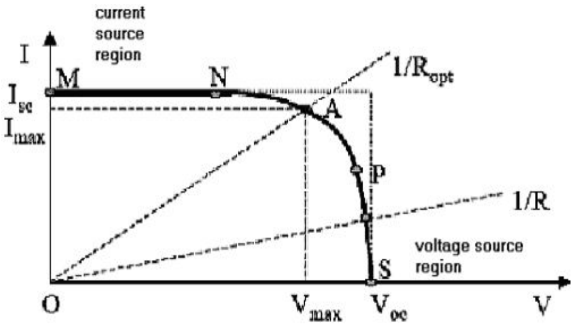
typical V-I characteristic of solar cell is shown in Fig.



Solar Cell Characteristics

For a solar cell, the non-linear relationship means the maximum power point has to be determined by calculating the product of the voltage and output current. In order to extract maximum power from the solar cell, the solar cell must always be operated at or very close to where the product of the voltage and output current is the highest. This point is referred to as the maximum power point (MPP) and it is located around the 'bend' or 'knee' of the I-V characteristic. The operating characteristic of a solar cell consists of two regions: the current source region and the voltage source region. In the current source region, the internal impedance of the solar cell is high and this region is located on the left side of the current-voltage curve. The voltage source region, where the internal impedance is low, is located on the right side of the current-voltage curve. As can be observed from the characteristic curve, in the current source region, the output current remains almost constant as the terminal voltage changes and in the voltage source region, the terminal voltage varies only minimally over a wide range of output current.According to the maximum power transfer theory, the power delivered to the load is maximum when the source internal impedance matches the load impedance. For the system to operate at or close to the MPP of the solar panel, the impedance seen from the input of the MPPT needs to match the internal impedance of the solar panel. Since the impedance seen by the MPPT is a function of voltage (V = I * R), the main function of the MPPT is to adjust the solar panel output voltage to a value at which the panel supplies the maximum energy to the load. However, maintaining the operating point at the maximum power point can be quite challenging as constantly changing ambient conditions such as irradiance and temperature will vary the maximum power operating point. Hence, there is a need to constantly track the power curve and keep the solar panel operating voltage at the point where the most power can be extracted.Irradiance is a characteristic related to the amount of Sun energy reaching the ground, and under ideal conditions it is measured as 1000 W/m^2 at the equator. The sun energy on the earth is highest around the equator when the sun is directly overhead. Some important magnitudes related to irradiance include the spectral irradiance, irradiance and radiation. Spectral irradiance is the power received by a unit surface area at a particular wavelength, while irradiance is the integral of the spectral irradiance extended to all wavelengths of interest. Radiation is the time integral of the irradiance extended over a given period of timeIn designing PV systems, the main concern is the radiation received from the sun at a particular location at a given inclination angle and orientation and for long periods of time. Since solar radiation is the energy resource of the solar panel, the output of the panel is significantly affected by changing irradiance. The I-V and P-V characteristics of a solar cell including the effects of irradiance are shown in Fig.

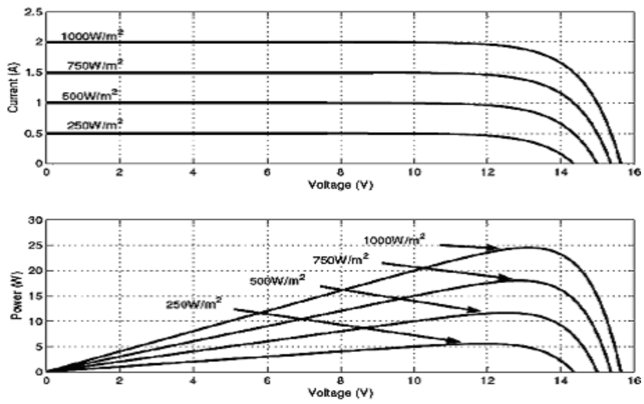


Fig : The I-V and P-V characteristics of a solar cell including the effects of irradiance

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IMPACT OF THE DC COMPONENTS ON PV SYSTEMS

A typical three-phase transformerless PV inverter system is shown in Fig. 1. 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 project, 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, which comprises a current loop and a dc-link voltage loop in the synchronous rotational frame, is a relatively common control strategy in three-phase PV inverters [25].

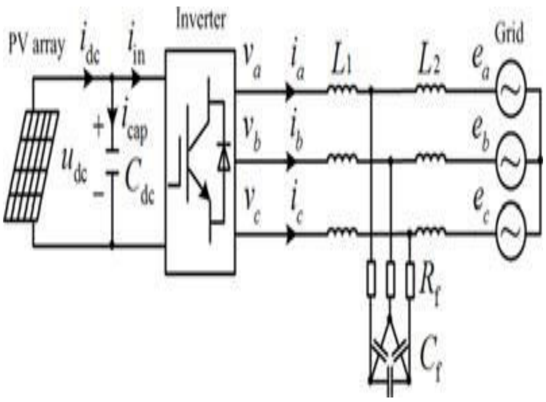

Fig. 1 Transformerless three-phase PV inverter system

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 (*abc*), two-phase stationary ($\alpha\beta$), and two-phase rotational (*dq*))

$$\begin{cases} F_a = F_{a0} + F_{a1} \\ F_b = F_{b0} + F_{b1} \\ F_c = F_{c0} + F_{c1} \end{cases}, \begin{cases} F_\alpha = F_{\alpha 0} + F_{\alpha 1} \\ F_\beta = F_{\beta 0} + F_{\beta 1} \end{cases}, \begin{cases} F_d = F_{d0} + F_{d1} \\ F_q = F_{q0} + F_{q1} \end{cases} \quad (1)$$

Where the subscript 0 denotes the dc component and the subscript 1 denotes the line-frequency component. Note that the zero component in conventional coordinate transformation is not taken into account due to the three-wire system. If there are dc components in the *abc*coordinate, they will also exist in the form of dc or line-frequency components in $\alpha\beta$ and *dq* coordinates, respectively.In a three-phase three-wire system, there is no current flowing through the neutral point and hence

$$\begin{cases} F_{a0} + F_{b0} + F_{c0} = 0 \\ F_{a1} + F_{b1} + F_{c1} = 0. \end{cases} \quad (2)$$

With (1) and (2), the coordinate transformations of the dc components from *abc*coordinate to $\alpha\beta$ and *dq*coordinate can be expressed as

$$\begin{bmatrix} F_{\alpha 0} \\ F_{\beta 0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} F_{a0} \\ F_{b0} \\ F_{c0} \end{bmatrix} = \begin{bmatrix} F_{a0} \\ \frac{\sqrt{3}}{3} F_{b0} - \frac{\sqrt{3}}{3} F_{c0} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} F_{d1} \\ F_{q1} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} F_{a0} \\ F_{b0} \\ F_{c0} \end{bmatrix} = \begin{bmatrix} F_{a0}\cos\theta + \frac{\sqrt{3}}{3}(F_{b0} - F_{c0})\sin\theta \\ \frac{\sqrt{3}}{3}(F_{b0} - F_{c0})\cos\theta - F_{a0}\sin\theta \end{bmatrix} \quad (4)$$

Where θ is the angle between the *dq*coordinate and *abc*coordinate, for example, the grid angle in a grid-voltage oriented vector control.

As seen in (3) and (4), by the coordinate transformation, $Fa0$,$Fb0$, and $Fc0$ (dc components) in the stationary *abc*frame can be

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transformed into $F\alpha 0$ and $F\beta 0$ in the stationary $\alpha\beta$ frame and then $Fd1$ and $Fq1$ (line-frequency) in dqframe. Therefore, the voltage and current in the control loop of each frame will contain both dc and line-frequency components. The synthesized vector $\boldsymbol{F}$ of dc components can be decomposed in the frames shown in Fig. 2, where $\boldsymbol{F}$ is a stationary vector. Since the dqframe rotates anticlockwise, the dc component in the synchronous dqframe appears in the form of a negative-sequence line-frequency component.According to the instantaneous power theory [26], [27], the system active power $pac$and reactive power qaccan be expressed in (5) and (6) in the dqframe, where the mark "·" and the mark "×" are the inner and outer product of vectors, respectively

$$p_{ac} = \frac{3}{2}\begin{bmatrix} U_d \\ U_q \end{bmatrix}^{\mathrm{T}} \cdot \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{3}{2}\begin{bmatrix} u_{d0}+u_{d1} \\ u_{q0}+u_{q1} \end{bmatrix}^{\mathrm{T}} \cdot \begin{bmatrix} i_{d0}+i_{d1} \\ i_{q0}+i_{q1} \end{bmatrix}$$

$$= \frac{3}{2}\Big(\underbrace{u_{d0}i_{d0}+u_{q0}i_{q0}}_{\text{DC component}} + \underbrace{u_{d0}i_{d1}+u_{d1}i_{d0}+u_{q0}i_{q1}+u_{q1}i_{q0}}_{\text{Line-frequency fluctuation}}$$

$$+ \underbrace{u_{d1}i_{d1}+u_{q1}i_{q1}}_{\text{2nd fluctuation}} \Big) \qquad (5)$$

$$q_{ac} = \frac{3}{2}\left| \begin{bmatrix} U_d \\ U_q \end{bmatrix}^{\mathrm{T}} \times \begin{bmatrix} I_d \\ I_q \end{bmatrix} \right| = \frac{3}{2}\left| \begin{bmatrix} u_{d0}+u_{d1} \\ u_{q0}+u_{q1} \end{bmatrix}^{\mathrm{T}} \times \begin{bmatrix} i_{d0}+i_{d1} \\ i_{q0}+i_{q1} \end{bmatrix} \right|$$

$$= \frac{3}{2}\Big(\underbrace{u_{q0}i_{d0}-u_{d0}i_{q0}}_{\text{DC component}} + \underbrace{u_{q0}i_{d1}+u_{q1}i_{d0}-u_{d0}i_{q1}-u_{d1}i_{q0}}_{\text{Line-frequency fluctuation}}$$

$$+ \underbrace{u_{q1}i_{d1}-u_{d1}i_{q1}}_{\text{2nd fluctuation}} \Big). \qquad (6)$$

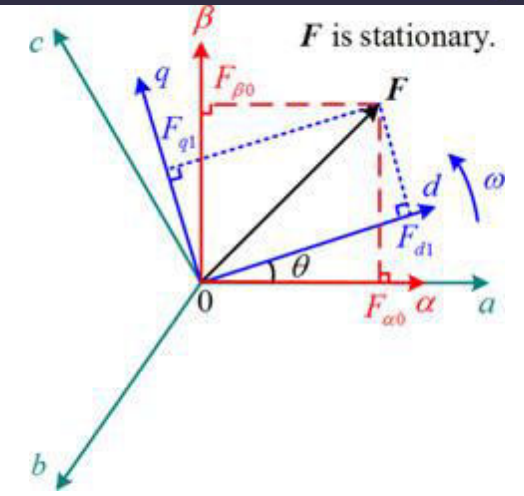

Fig. Coordinate transformation of dc components

As seen, both the active and reactive power contains a constant dc power (desired), a line-frequency, and a second-order power fluctuation due to the dc component in the voltage and current (undesired). Further, with grid-voltage orientated vector control under unity power factor operation for PV applications, where $uq0$ = 0, $iq0$ = 0, (5), and (6) can be simplified to (7) and (8) if assuming the second-order fluctuations is negligible compared to the other two components

$$p_{ac} = \frac{3}{2}\Big(\underbrace{u_{d0}i_{d0}}_{\text{DC component}} + \underbrace{u_{d0}i_{d1}+u_{d1}i_{d0}}_{\text{Line-frequency fluctuation}} \Big) \qquad (7)$$

$$q_{ac} = \frac{3}{2}\Big(\underbrace{u_{q1}i_{d0}-u_{d0}i_{q1}}_{\text{Line-frequency fluctuation}} \Big). \qquad (8)$$

As seen in (7) and (8), line-frequency fluctuations will appear in both active power pac and reactive power qac when the dc components in the ac voltage and ac current are considered. The reactive power only circulates in the inverter phase legs at the ac side and does not affect the dc side. In comparison, the line-frequency active power fluctuations will impact the dc-link power, e.g., causing voltage ripple in the dc-link [15], which in return will generate a second-order harmonic in the ac current [28]. Therefore,

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effective solution to minimize the dc component is important apart from the reasons given in the introduction part. The impact of dc components on PV systems is illustrated in Fig. 3.

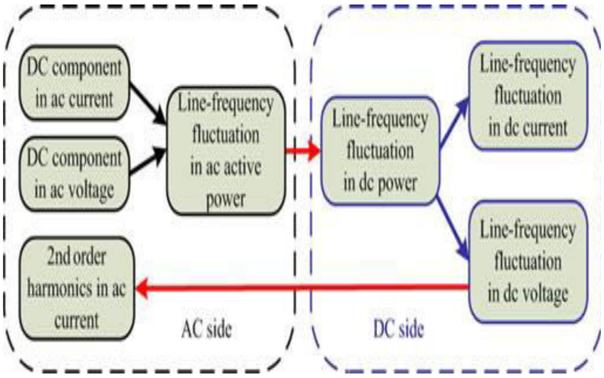

Fig. Influences of dc component on PV systems

SIMULATION RESULTS

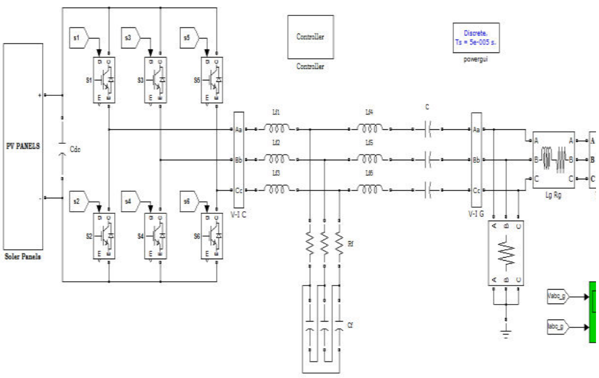

Fig.Transformerless three-phase PV inverter system Simulation

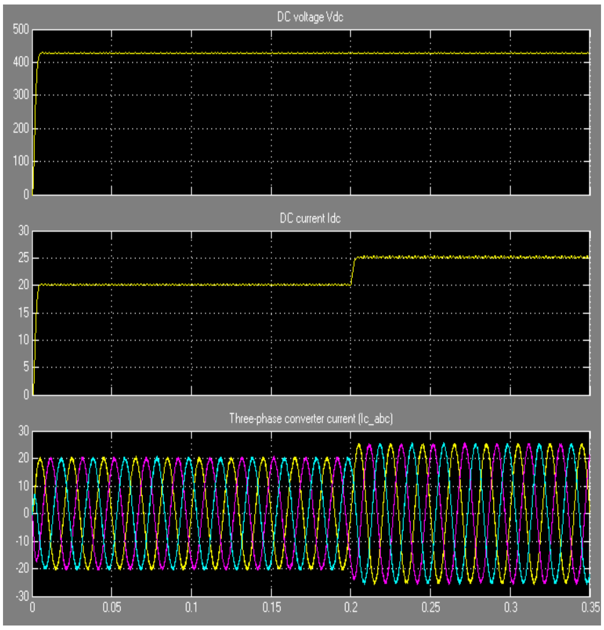

Fig PV output voltage and current

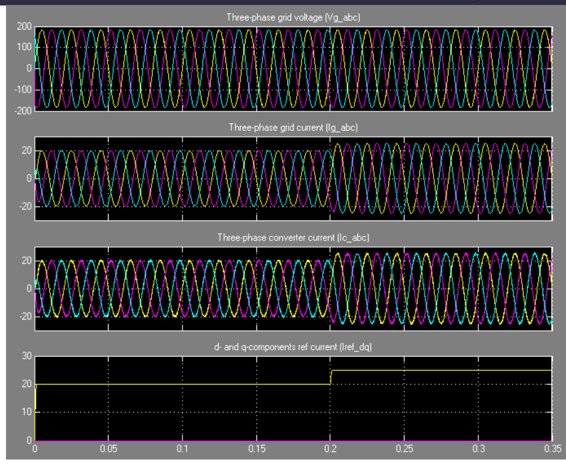

Fig with DC component minimization strategy 1

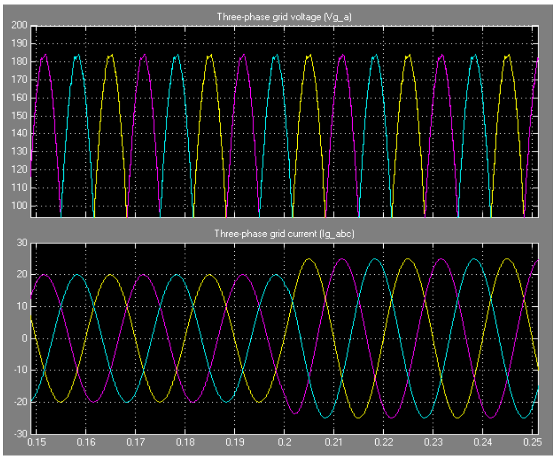

Fig. without DC component minimization strategy

CONCLUSION

This project has presented an effective method to minimize the dc component in a three-phase transformerless grid-connected PV system. The dc component can introduce line-frequency power ripple in the system and further cause dc-link voltage ripple and second-order harmonics in the ac currents. A software based “virtual capacitor” approach has been implemented to minimize the dc component via a feed-forward of the dc component. The dc component can be accurately obtained using the sliding window iteration and double time integral even under frequency variation and harmonic conditions. A PIR controller has been designed to enable the precise regulation of both the dc and line-frequency components in the *d-q* frame. The proposed method can be well adopted in the existing PV

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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.

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