최대출력추종 제어를 포함한 단상 태양광 인버터를 위한 새로운 입출력 고조파 제거법
A Novel Input and Output Harmonic Elimination Technique for the Single-Phase PV Inverter Systems with Maximum Power Point Tracking

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ABSTRACT
This paper proposes a grid-tied photovoltaic (PV) system, consisting of Voltage-fed dual-active-bridge (DAB) dc-dc converter with single phase inverter. The proposed converter allows a small dc-link capacitor, so that system reliability can be improved by replacing electrolytic capacitors with film capacitors. The double line frequency free maximum power point tracking (MPPT) is also realized in the proposed converter by using Ripple Correlation method. First of all, to eliminate the double line frequency ripple which influence the reduction of DC source capacitance, control is developed. Then, a designing of Current control in DQ frame is analyzed and to fulfill the international harmonics standards such as IEEE 519 and P1547, 3rd harmonic in the grid is directly compensated by the feedforward terms generated by the PR controller with the grid current in stationary frame to achieve desire Total Harmonic Distortion (THD). 5-kW PV converter and inverter module with a small dc-link film capacitor was built in the laboratory with the proposed control and MPPT algorithm. Experimental results are given to validate the converter performance.

Index Terms – Dual Active Bridge, Active power decoupling, bidirectional DC-DC Converter, and Ripple rejection

1. INTRODUCTION
Photovoltaic (PV) energy has become one of the most popular sustainable energy sources nowadays because of government incentives and continuous cost reduction. In high-power grid-tied PV systems, galvanic isolation between the PV panel and the grid is required to prevent electric shock on PV panel due to insulation damage and to suppress leakage current. Hence, compared to single-stage inverter, the 2-stage single phase inverter integrated with high frequency-link (HFL)-based dc–dc converters has advantage of providing galvanic isolation between the PV panel and the grid without using bulky line-frequency transformer. However, in single phase two-stage PV system with dc–dc stage, electrolytic capacitors are used as the dc-link energy buffers between dc–dc stage and inverter stage or/and at parallel to the PV side to suppress the double-line frequency (2ω) power. Though electrolytic capacitor has high capacitance density, it has been considered as a particularly unreliable component, which is on average 30 times less reliable than non-electrolytic capacitor under identical conditions. Therefore, capacitance reduction is highly desirable in order to achieve high reliability with non-electrolytic film capacitor. However, the small dc-link capacitance will make the converter suffer from large 2ω voltage ripple on the dc-line and this voltage ripple will propagates to the PV side and it will deteriorate the MPPT performance and decrease the MPPT efficiency.

In [1] the DC active filters have been proposed to eliminate the input ripple current. In this method, the additional DC chopper circuit is introduced to inject the ripple current. The main drawback of this approach is that it requires an extra switching device and increase the size of system. In another approach [2], the ripple current is reduced by using a current-loop control without using external circuit. However, this technique is not capable of reducing the DC link capacitors. Moreover, it uses a large electrolytic capacitor for the DC link. A method in [3] has realized the DC active filter function without adding extra active devices. It connects the decoupling capacitor to the center tap of the isolation transformer and us es the common-mode voltage to decouple the ripple power. However, this method increases the current rating of the transformer.

For grid connecting system, grid current control is essential part .There are two most common method to control the current one is Stationary Reference frame (SRF) and other one is rotatory reference frame (RRF). In the RRF controllers, since the transformation turns ac quantities into dc quantities, Simple PI controller can provide a good control performance. The design process of the PI controller is simple, and it provides satisfactory dynamic and steady-state performance. Also, as the system variables are converted to dc quantities, the control loop has no dependence on the system frequency.

Simple PI controller for current control in RRF have an inadequate competence in compensating the low order ac ripple components which will replicate at inverter output current that is injected into the grid. Therefore, it cause high value in THD and doesn't satisfy a certain limit according IEEE 519 and P1547 harmonic standard. In order to fulfill the international harmonics standards and meet the required THD value for the inverter output under the distorted grid condition, the use of harmonic controller is essential.

In this paper, the two-loop voltage-feedback controller for the power-decoupling technique is proposed in at the DC-DC converter side as shown in Fig 1. One loop is for the DC-link ripple elimination, which replaces the current controlled ripple reduction loop. This loop includes a band pass filter (BPF) to reject the DC component of the DC link and bypasses the ripple. PI controller of ripple rejection loop is designed to mitigate the 120-Hz ripple component. The second loop is used to pass the 120-Hz component of the power decoupling capacitor voltage to freely oscillate around a specified average. The leverage of the proposed control method is that there is no need to have a 120-Hz estimated reference synchronized with the inverter PLL so its independent from inverter control. Moreover, the PV side capacitance is effectively reduced by the proposed method. The low-frequency ripple-free maximum power point tracking (MPPT) is also realized in the proposed converter by using Ripple Correlation method. To fulfill the international harmonics standards such as IEEE 519 and P1547, the quality of a grid connected inverter current must satisfy a certain level of THD. In order to achieve the desire THD value for the inverter output current under the non-sinusoidal grid condition, the use of harmonic controller is mandatory. So, to accommodate this issue feedforward harmonic compensation method is used to eliminate the 3rd order harmonic in the inverter.

2. CONTROLLERS DESIGN FOR DAB
For the designing DAB Controller i-e DC-link voltage control and controller for double line harmonic elimination, Control to output and input voltage transfer function is required. Control to input Voltage transfer function G_{VDC} and control to output voltage transfer function G_{VDC_link} is acquired from [3] which is shown in following equation;

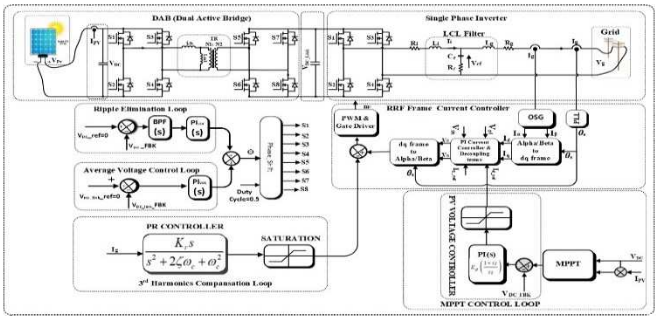


Fig.1 DC-AC power conversion photovoltaic system with their complete control loops

$$G_{V_{DC\_link}} = \frac{V_{DC}}{n\omega L_k}\left(1-2\frac{|\delta|}{\pi}\right)\left(\frac{R_L}{1+C_{DC\_Link}R_L s}\right) \quad (1)$$

Similarly control to input voltage transfer function is given by Eq. (2).

$$G_{V_{DC}} = -\frac{V_{DC\_link}}{n\omega L_k}\left(1-2\frac{|\delta|}{\pi}\right)\left(\frac{R_L}{1+C_{DC}R_L s}\right) \quad (2)$$

In the proposed double line frequency ripple elimination method there are two controllers. One is the PI controller to compensate the double line frequency ripple and the other is another PI controller to regulate the DC link voltage. As explained earlier, the transfer function of the DAB converter at each direction is given by Eq. (1) and Eq. (2).

The block diagram of the proposed control loop is shown in Fig.1 In Fig.1 shows the double line frequency ripple compensation loop, where BPF(s) and $PI_{VDC}(s)$ is the band pass filter and the PI controller. Another PI controller shown as $PI_{VDC\_link}(s)$ is used for regulating the average voltage across the DC link capacitor.

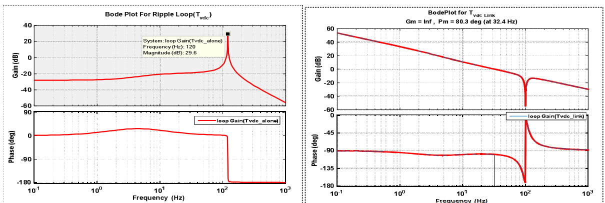
At first, the double line frequency ripple compensation loop is designed. In designing the BPF the center frequency is selected at 120 Hz and the value of the damping factor is selected very low to get a higher gain at 120Hz.

Then the PI controller needs to be designed to reject all the components other than 120Hz by allowing a higher gain at 120Hz. Thus, the loop gain (T_{VDC}) for the double line frequency ripple compensation loop can be represented as Eq. (3).

$$T_{(VDC)} = BPF(s) * PI_{VDC} * G_{VDC} \quad (3)$$

Where G_{VDC} is control to output transfer function in Eq. (3). The controller is designed by using MATLAB and the resulting Bode plots are shown in Fig.2(a). The parameters for the PI controller are K_p = -0.03 and the time constant τ = 10e-3. It can be clearly seen from the Bode plot that the design of the controller has been accomplished as expected. It shows very high gain only at 120Hz. The loop gain is 29.6 dB at 120 Hz, which is adequate to eliminate 120Hz component.

The voltage controller for the DC link voltage is designed by using the block diagram shown in Fig. 1. The main consideration for this controller is to allow the 120 Hz AC ripple at the DC link voltage V_{DC_Link} by controlling it loosely. Hence, the bandwidth of the controller is selected to be as lower than 120Hz as possible. Fig.1 shows the control block diagram of the whole system including the double line frequency ripple compensation loop.



(a) (b)

Fig. 2. Bode Plot of: a) T_{vdc} b) $T_{vdc\ link}$

The loop gain T_{VDC_link} for average voltage controller is shown as Eq. (4). Where, $G_{VDC\text{-}link}$ is the plant transfer function shown in Eq. (1) and $PI_{VDC\text{-}link}$ is the transfer function of the PI controller.

$$T_{(VDC\_link)}(s)\Big|_{Vdc\_ref=0} = \frac{PI_{VDC\_link}G_{VDC\_link}}{1+BPF(s)*PI_{VDC}*G_{VDC}} \quad (4)$$

By using MATLAB, the controller is designed with the procedure mentioned above. The Bode plot of the loop gain $T_{VDC\_link(s)}$ is shown in Fig. 2(b). The parameters for the PI controller is obtained as Kp = 0.003 and τ = 30e-3. The bandwidth of the DC link voltage controller is 32.4Hz and the phase margin is 80.3deg.

3. CONTROLLERS DESIGN FOR INVERTER

Fig.1shows the general block diagram of a single-phase grid-connected inverter controlled in DQ frame**.** where a single-phase H-bridge inverter injects power to the grid through a passive LCL filter. The grid voltage and current are fed back to the controller. In the Rotatory Reference Frame(RRF) controllers, since the transformation turns ac quantities into dc quantities, Simple PI controller can provide a good control performance. As shown in Fig.3(b), current controller required an orthogonal Signal Generator (OSG) block to generate the α & β axis component of the grid current. For this research we select Second-Order Generalized Integrator (SOGI), Since it generates the OSG signals perfectly that's why it used extensively. Furthermore, it provides good attenuation or filtering capability over the harmonic components. In addition, Phase-Locked-Loop (PLL) is used in this scheme to synchronize the controller to the grid voltage. This controller consists of PI controllers, decoupling terms, and feed forwards in both D and Q axes. In order to cancel the effect of decoupling terms and grid voltage term present in the plant, these terms should be added in the current controller, which adequately cancels each other. Based on this phenomenon the current controller can be simplified as shown in Fig 3(b). Plant transfer as given below,

$$G_P(s) = \frac{1}{(L_i+L_g)+(r_i+r_g)} \quad (5)$$

From Fig3(b) loop gain can be expressed as;

$$G_{ol}(s) = G_i(s)*G_{PWM}(s)*G_P(s) \quad (6)$$

By using MATLAB, the controller is designed. The Bode plot of the loop gain $G_{ol\ (s)}$ close loop are shown in Fig. 3(a). The parameters for the PI controller is obtained as Kp = 9.85 and K_i= 157.7 The bandwidth of the current controller is 697Hz and the phase margin is 89.8deg.

RRF current controller for grid current control under the conditions of 30Vp 120Hz ripple at the DC-link, current control successfully track the reference but there is dominant 3rd harmonic in DC feedback and Grid current which makes THD higher. In order to fulfill the international harmonics standards such as IEEE 519 and P1547, additional controllers for the harmonic compensation are added to ensure the quality of the inverter output under non-sinusoidal grid condition as shown in Fig.1 In this research, current controller is in RRF and the PR controller deal the current harmonics in SRF. The PR controller detects the output under non-sinusoidal grid condition as shown

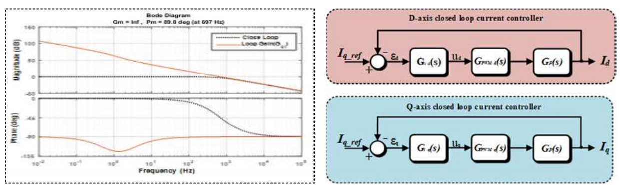


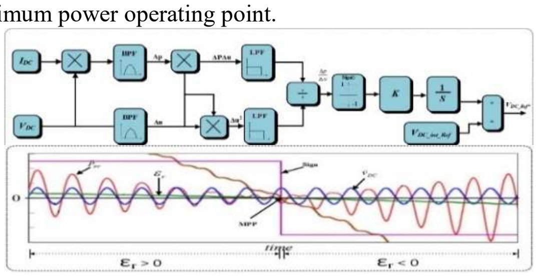
Fig.3 (a) Bode plot loop Gain and Close loop (b) Simplified Current controller in Fig.1 In this research, current controller is in RRF and the PR controller deal the current harmonics in SRF. The PR controller detects the harmonic information from the injected inverter current into the grid and is directly compensated after the inverse park's transformation to the PWM voltage command to compensate the desire harmonic.

4. Maximum power point Tracking Algorithm

This research used RCC control method for MPPT. RCC-MPPT technique is the one which have the following advantages: parameter-insensitive MPPT of PV systems,very fast convergence to reach maximum power point MPP, simple and straightforward circuit implementations and well-explained theoretical analysis.

In RCC-MPPT, low frequency component is mandatory component for tracking MPP. So most of the cases low frequency is inject from outside. In this approach instead of feeding the plant with sinusoidal probing signals, the control input will be obtained by using the low frequency component induced by the 2nd stage inverter at the PV side. So, there is no need of generating the low frequency perturbation by controller. This low frequency must be extracted by filter, band-pass filter is used as shown in Fig.4(a) .which is the replacement of high-pass filter, usually used in the RCC-MPPT structure. The DC-source voltage can be significantly switching noise; therefore, the alleviation of noise effect is done by low pass filter. Operations performed within the MPPT algorithm are shown in Fig 4(a). The MPPT algorithm has sense signals V_{DC} and I_{DC} as inputs and from there product got P_{PV}. $V_{perturb}$ is final a perturbation in reference voltage signal. At every switching instant, this algorithm comprises of: band-pass filter for filtering the signals V_{DC} and P_{PV} to get the sinusoidal signal $\tilde{v}_{DC}$ and $\tilde{p}_{PV}$ respectively. Multi-plying the filtered signals and pass through the low pass filter to remove switching noise . After that dividing this signal by $\tilde{v}_{DC}^2$ signal to get ∂p/∂v ,Checking the sign of this residue function for getting information of operating point moving toward or away from MPP and K is multiplying factor which control the speed of reaching MPP. Finally integrating the result to get perturbation in Voltage reference.

The quantity sign(ε_r) is a clear indication of the region where the PV panel is operating as clearly shown in Fig.4(b): if (ε_r)>0 means $\tilde{p}$ and $\tilde{v}$ are in-phase agreement. The operating point is on the left side of the MPP on the (I–V) characteristic. if (ε_r)<0 means $\tilde{p}$ and $\tilde{v}$ are out of phase. The operating point is on the right side of the MPP on the I–V characteristic. The knowledge of the instantaneous operating point region makes it possible to change the PV voltage reference in order to approach the maximum power operating point.



4.

Fig.4 (a) Block Diagram RCC-MPPT method (b)waveform at before, after and at the MPP

EXPERIMENTAL RESULTS

For the experimental verification of the proposed method, a 5kw DAB converter and a single phase full-bridge inverter have been implemented as a DC-AC inverter. Experimental result for the hardware prototype with ripple elimination loop are acquired at 5kw rated output power in order to verify the practicality of

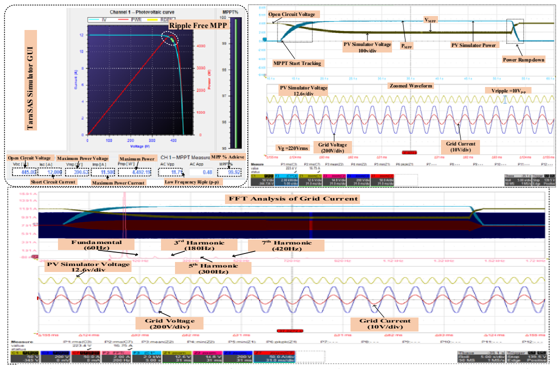


Fig.5 (a) TeraSAS I-V/P-V Curve (b)MPPT Experimental result (c) Experimental result with Grid Current FFT

proposed control method.Fig.5 illustrate the steady-state experimental results when the double line frequency elimination, current controller, harmonics controller, MPPT algorithm is enabled, and it suppresses the double line frequency ripple on the 380 V high-voltage bus and to alleviate the ripple pollution form the input DC source. As shown in Fig.5 at 4.5kw power, ripple at V_{DC} is around 5v peak at the DC source(PV Simulator) side, which demonstrate that ripple is successfully eliminated from the input side with low capacitor values of 200uF at DC input side and 400uF at the DC link. Furthermore, experimental result are also shown that controller successfully controlled the average voltage 400v at the DC link and inverter side current controller controlled the current. As clearly shown from FFT of grid current, PR controller for 3rd harmonic successfully eliminated the harmonic. Fig. 5 shows the steady-state and dynamic performance of MPPT waveforms, while Fig.5 depicts the corresponding MPPT trajectories of P–V and I–V curves capture by GUI of TERASAS Software of PV simulator. In steady state, the PV voltage ripple around the MPP is less than 5V_p at 4.5kW. This small variation ensures the MPPT efficiency higher than 99.2%.

In order to obtain a similar ripple at PV Simulator without double line frequency ripple elimination method, the capacitance should be 5000µF,which is more than 25 times larger than that of the proposed system (200 µF). The DC Source (PV Simulator) side capacitor reduction is calculated as (5-0.20)/5 = 96%. [5mF capacitor is required if we have 5v_p 120Hz]. On the other hand, DC link Side, we allow 30Vpeak ripple, so we required only 400uF Capacitor. We can make this ripple 20Vpeak (380v-420v) but then capacitor values required is 800uF

5. CONCLUSION

This paper has presented a novel Control for double line ripple elimination method for the two-stage PV grid connecting single-phase DC-AC power conversion system which fulfil the IEEE 519 and P1547 standard of harmonics by using the feedforward harmonics compensation method at inverter side control. The main advantage is that it does not require additional circuit to reduce the ripple at the DC source side of the converter. Ripple reduction capability of the proposed technique the film capacitor can be employed, and the lifespan of the DC-AC conversion system can be extended.

References

[1] J. Riedel, D. G. Holmes, B. P. McGrath and C. Teixeira, "Active Suppression of Selected DC Bus Harmonics for Dual Active Bridge DC–DC Converters," in IEEE Transactions on Power Electronics, vol. 32, no. 11, pp. 8857-8867, Nov. 2017.

[2] C. Liu and J. Lai, "Low Frequency Current Ripple Reduction Technique with Active Control in a Fuel Cell Power System with Inverter Load," in IEEE Transactions on Power Electronics, vol. 22, no. 4, pp. 1429-1436, July 2007.

[3] A.Saghir, Choi Woojin "Power Decoupling Control of the Bidirectional Converter to Eliminate the Double Line Frequency Ripple," in ICPE 2019.