V2G Grid-Tied Inverter System based on LCL Filter with Control Strategy

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Abstract. Vehicle-to-Grid (V2G) technology has been hotly discussed in recent years because of its broad prospects in load transfer and regulation. This article proposes a grid-connecting inverter system with LCL filter and control strategy for use in electric vehicle (EV) applications. A review of designation of LCL filter's parameter and mathematic modelling is given in part 2. An explanation of control strategy is given in part 3. Part 4 gives a comparison of active damping and passive damping control strategies with calculated parameters and gives the simulation results based on MATLAB. The results show with parameters calculated with method in article, both strategies have good tracking performance and similar response time. For the critical steady state, passive damping shows higher amplitude of oscillation. This phenomenon gives a new view proof that active damping method is superior than passive damping control strategy. The article is also of some reference value for determining LCL filter's parameters and proportional, integral coefficient of similar control strategy.

Keywords: V2G, Grid-connecting inverter, Active damping, Phase lock loop, LCL filter.

1. Introduction

With the growing of world's environmental awareness and the general depletion of oil and fossil fuels, people turn their attention to the application of clean energy. In recent decades, renewable energy has become the focus of attention around the world. Modern research has enhanced new technologies for harnessing renewable resources such as solar energy, wind energy, hydroelectric power plants, etc. [1].

However, with the deepening involvement of renewable sources, the dynamic performance of the power grid can be affected. Limited by uncontrollability of the natural environment, the REG causes additional challenges to power grid on regulation and increases cost on spinning reverse aspect. On the contrary, the V2G technology can play a positive role in load shifting, regulation, and spinning reverse aspects, improve the DSM (Demand side management) and reduce the number of conventional standby generator sets and save cost [2]. What's more, there is inherently complementation trend between V2G and REG.

For a power generation and grid-connected technology, power quality is a major concern for the power grid. Research on the effect of V2G technology at substation 33kV/11kV located at Amman city proofs the THD increases as the penetration level increases. Although the total voltage distortion and the individual voltage distortion hadn't exceeded the IEEE standards, study on improve electricity quality of grid-tie inverter is still necessary [3].

This paper design of GTI based on third order LCL filter with PLL and double closed loop control strategy. The arrangement of rest parts of this paper are as follows: section 2 and 3 will introduce the LCL filter and control logics respectively. Section 4 will give a comparation of active and passive damping's performance.

2. LCL Filter with 3p3l Inverter

2.1. Review of LCL filter

With the development of PV and V2G technologies, several neoteric topologies have been proposed. Compared to those new designs, three-phase-three-legs inverter has less and symmetric

power switches and simple and stable structure, which is suitable to build a model as basic configuration.

As a third order filter, LCL filter performs a better suppression effect on high frequency harmonics compared to traditional L filter with same inductance. The comparison of L filter and LCL filter's magnitude versus frequency response curve is shown in figure 1.

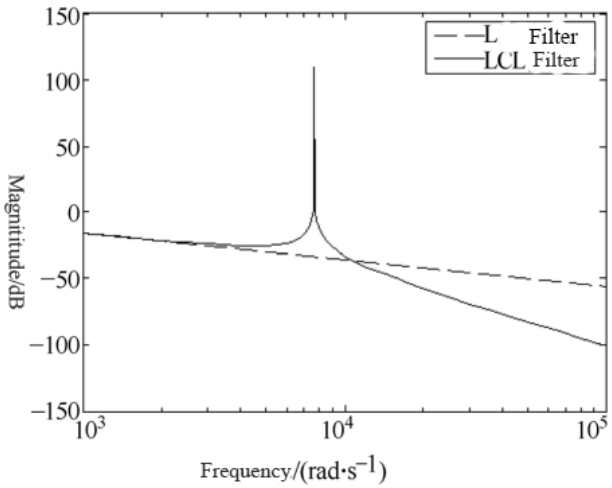


Fig. 1 Frequency response comparison of L and LCL filter with same inductance value [4]

Through simulation given in research, figure 1 shows for frequency lower than resonance, the LCL and L filter behaves almost same filtering effects [4]. But for frequency higher than LCL's resonance, the LCL decaying with -60dB/dec and L filter with same inductance decaying with -20dB/dec. This high frequency filter performance determines LCL filter fit for higher-frequency, higher-power application scenarios. Above all, for the same request on filtering effects, LCL need less inductance, which markedly save cost for total system; furthermore, the good performance of high frequency harmonics restrain ability can achieve the requirement of power grid; last, the rear inductor connected to the grid side can also restrain the inrush current.

2.2. Model and analysis of LCL filter

Usually, the impedance of LCL filter is reciprocal to frequency of flowing current. While because of the current divided by capacitor, the total current control system becomes more complicated. And some high-order harmonics of current will cause resonance and affects the stability of system seriously. Generally, this problem is solved by adding damping on the basis of the existing control strategy.

The damping can be divided into active and passive. The passive damping resistor is usually series connected with the capacitor. In this case, the transfer function of LCL filter is given by formula (1).

$$G_{LCL}(s) = \frac{i_2(s)}{U_{in}(s)} = \frac{sCR_c}{s^3L_1L_2C+s^2(L_1+L_2)CR_c+s(L_1+L_2)} \quad (1)$$

Where L_1 refer to inductance on inverter side and L_2 for grid side. grid side. C is filter capacitance and R_c refers to parasitic or series resistance on capacitor branch.

When no damping is added, the open-loop pole of the system is located on the imaginary axis of the s plane. At this time, the system is in a critical stable state and is easily disturbed. After adding the damping resistor, the pole will shift to the left lead the system goes to steady state. Damping resistance usually setting with the half value of capacitive reactance on resonant frequency.

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1L_2C}} \quad (2)$$

In the high frequency band, the capacitive reactance decreases, and the series resistance will increase the impedance of the capacitor branch, causing the LCL high frequency filtering

performance to decrease. In the low frequency band, the resistor impedance is much lower than the branch capacitance, which has less impact on the low frequency gain of LCL. The passive damping method can better suppress the resonance peak and has low control difficulty, so it has been widely used in industry. However, it may cause huge heat generation, requiring additional heat sinks. Although the sensor is reduced, the cost may not be reduced in the long term due to the power loss caused by the resistance and the additional heat dissipation equipment. What's more, grid-connected inverter has extremely high requirements on power quality, so control strategies related to the active damping method are more widely used in grid-connected inverter. This method stabilizes the system by modifying the control algorithm, eliminates resonance, and avoids the loss problem of passive damping by increasing the complexity of the control.

In order to determine the parameters of LCL filters, Liu F analyzed the harmonic model of LCL filter under gird-connected operation, conclude the output ripple mostly depends on the inverter side inductor and current harmonics decaying with the ratio L_1/L_2 increasement in range (0,1) when capacitance is a constant [4]. It also mentioned the limitation of resonance frequency, however, using the active damping control can also avoid the influence of resonance.

3. Control Method

3.1. Model and analysis of control logic

Figure 2 shows a dual closed-loops current control structure diagram of a three-phase grid-tied inverter (GTI) system based on LCL filter with the grid-connected inductor current as the outer loop and the capacitor current as the inner loop. Through this control method, the anti-interference ability can be improved and reduced power losses compared to passive damping method. At the same time, the original good filtering characteristics of LCL are guaranteed [5, 6]. The command current $i_{d,ref}=i_{L2d}$, $i_{q,ref}=i_{L2q}$. Using proportional integral controller and SPWM method controls the power switch, makes this GTI with LCL filter output current in-phase with grid voltage. Ensuring the current total harmonic distortion comply with standard as IEEE 929-2000.

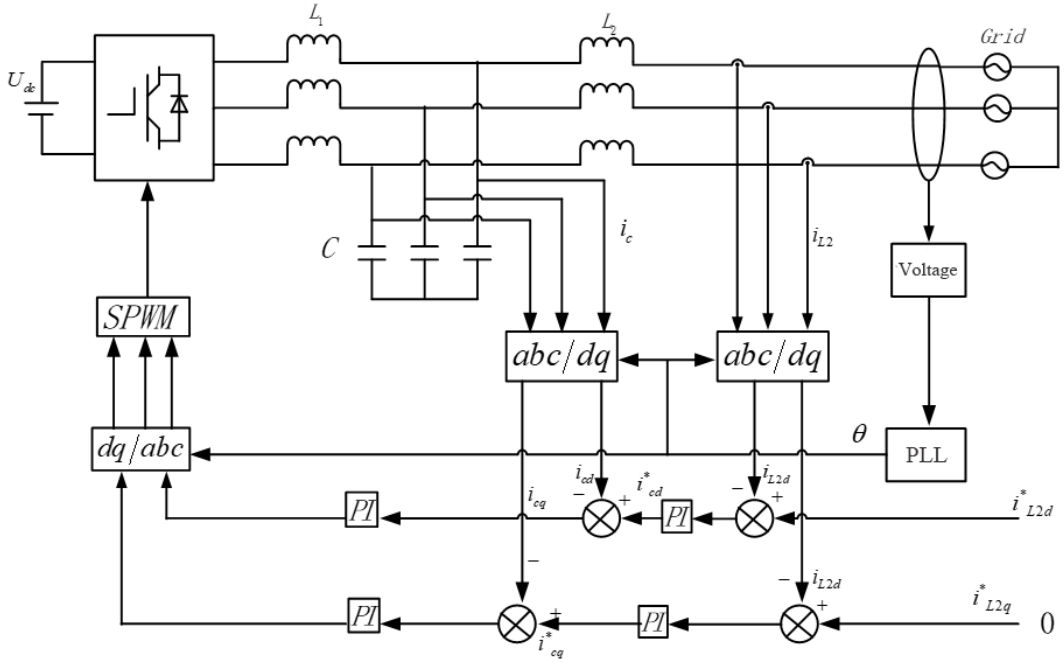


Fig. 2 Direct current control block diagram of three-phase grid-connected inverter (Photo/Picture credit: Original)

In order to reach astatic control, convert the abc axis signal (sinusoidal alternating component in three-phase stationary coordinate system) into dq axis (Two-phase DC flow in synchronous rotating coordinate system) is necessary. The transfer matrix is as follow.

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = m \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ -\sin\theta & -\sin\theta\left(\theta - \frac{2}{3}\pi\right) & -\sin\theta(\theta + \frac{2}{3}\pi) \\ -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3)$$

Where m is a parameter depends on requirement, if same amplitude is wanted, the m=2/3, if same power wants to be remained, m=sqrt(2/3).

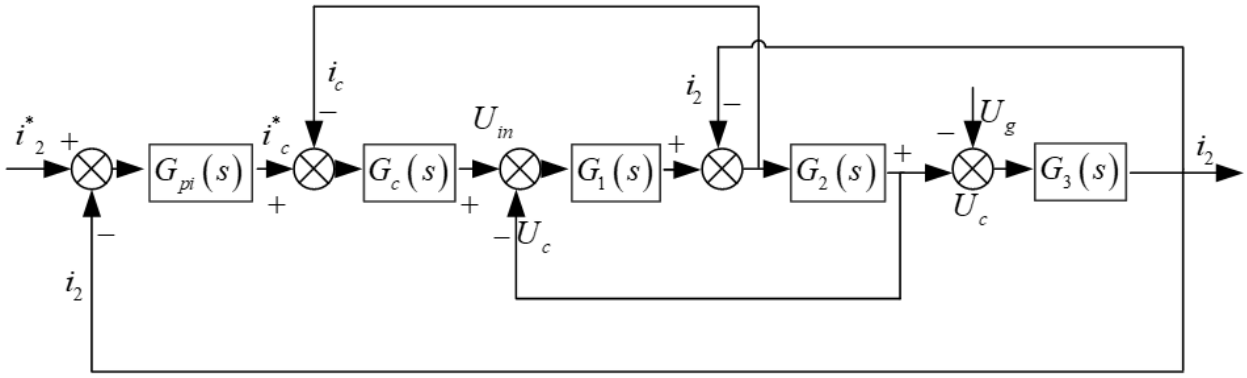


Fig. 3 Current double closed-loop control strategy based on i_c, i_2 (Photo/Picture credit: Original)

According to figure 3 the transfer function of control system is:

$$G(s) = \frac{i_2}{i_2^* - i_2} = \frac{G_{pi}G_1(s)G_2(s)G_3(s)G_4(s)}{1 + G_1(s)G_2(s) + G_2(s)G_3(s) + G_1G_c} = \frac{X_0 s + X_1}{Y_0 s^4 + Y_1 s^3 + Y_2 s^2 + Y_3 s} \quad (4)$$

Where G1(s)=1/(L_1+R_1), G2(s)=1/Cs, G3(s)=1/(L_2s+R_2), Gc=K_c, G_{pi}=K_p+K_i/s, X_0=K_pK_c, Y_0=L_1L_2C, Y_1=L_2R_2C+ L_1R_2C+L_2K_cC, Y_3=R_1+R_2, Y_2=R_1R_2C+R_2K_cC+L_1+L_2.

3.2. Phase lock loop

The phase-locked loop (PLL) operates as a feedback mechanism. Its primary role is to ensure that the circuit's clock phase aligns with that of an external clock source. By enabling automatic synchronization between the output and input frequency signals, PLLs are commonly employed in closed-loop tracking systems.

The basic contemporary technologies used to achieve grid synchronization including: adaptive notch filter (ANF), adaptive band pass filter (ABPF), complex coefficient filter which also performs band pass characteristics. These techniques with frequency selection functions can not only extract the fundamental wave or the orthogonal component of a certain harmonic instantly, but also obtain the frequency and amplitude information instantly [7]. This makes it possible for third harmonic injection technology (Which is proved can significantly increase the utilization of DC link voltage) to continually working in closed-loop control systems [8].

This study utilizes MATLAB/Simulink to examine a single synchronous coordinate system software phase-locked loop, known as SSRF-SPLL. The components of SSRF-SPLL include a phase detector, a loop filter, and a voltage-controlled oscillator (VCO). The output from the VCO undergoes sampling and frequency division before being paralleled with a reference signal fed into the phase detector. This detector assesses the frequency variance between these two inputs and subsequently emits a DC pulse voltage. This pulse serves to adjust the VCO's frequency. The scope of this research is limited to scenarios where the SSRF-SPLL algorithm applies, specifically focusing on three-phase balanced conditions where the grid voltage comprises solely the positive sequence component. Additionally, the positions of the actual voltage vector and the PLL output voltage vector within the stationary two-phase αβ coordinate system and the synchronous dq coordinate system are depicted in Figure 4.

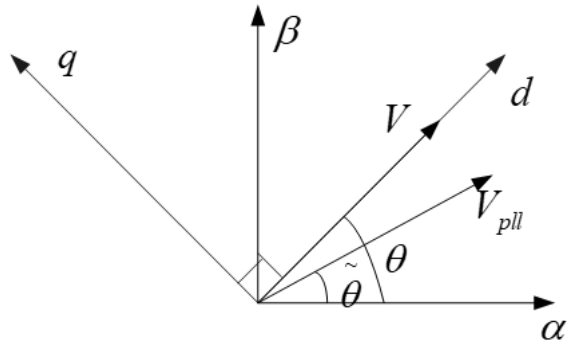


Fig. 4 Vector diagram of SSRF-SPLL (Photo/Picture credit: Original)

At the moment when the phase of grid voltage suddenly changes, the vector Vpll and V positions will inevitably differ. For this reason, appropriate closed-loop control must be adopted to ensure that the output of the phase-locked loop in phase with the real voltage.

The three-phase voltage should be transferred to alpha-beta axis with Clarks transform at first, then the vector in alpha-beta axis should be rotated to dq axis by Park transformation.

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = V \begin{pmatrix} \cos(\omega t + \varphi - \omega' t) \\ \sin(\omega t + \varphi - \omega' t) \end{pmatrix} = V \begin{pmatrix} \cos(\theta - \theta') \\ \sin(\theta - \theta') \end{pmatrix} \tag{5}$$

Where the output angular frequency ω'=dθ'/dt, due to the ω' remains unchanged after fully capturing the phase, ω't=θ'. So the value (θ-θ') is obtained. This deviation can be used to achieve feedback control of the system. When the phase difference Δθ is large, the process of phase locking the input three-phase voltage is a nonlinear process. V can be adjusted to a small enough value through negative feedback, which can achieve very small Δθ. When the phase difference Δθ is small, sin(θ-θ')≈θ-θ' the phase locking process can be approximated as a linear process. The size of V represents the difference between the input voltage phase and the output phase. V can be regarded as an error signal Δω after being passed through the PI regulator. Disturbance angular frequency ω_c and Δω 's sum is ω'. The final phase θ' is obtained after the angular frequency ω' is integrated. What's worth to mention is that the disturbance angular frequency ω_c is feedforward which is used to enhance the dynamic response speed of system. It needs to be set as a value to the exceptional static point.

Since the system is a second order system, the system can track the signal θ = ωt astatic. The output phase reproduces the input phase astatic, achieving complete phase locking [9].

4. Comparison of Active and Passive Damping Control Strategies

Given background parameters: DC bus voltage 700V as the voltage level after regulator, 380V/50Hz as the voltage level on the grid side. Switching frequency is set as 20kHz, rated output power of inverter is 10kW. According to section II.ii. the parameters of LCL filter can be specified: inverter side inductor L_1=1.75mH, grid side inductor L_2=0.44mH, filter capacitor C=10μF. Resonance frequency of filter is 2683Hz. For the outside inductor current loop, the transfer function is:

$$W(s) = \frac{K_{pwm}K_{pi}(\tau s+1)}{(L_1+L_2)\tau s^2(Ts+1)} \tag{6}$$

Where the K_{pwm} equals to half of V_{dc}, K_p=K_{pi} and K_i=K_p/τ. τ = hT in active control method. T=1/f_{sw}.

For Passive control method, there is only one control loop same to above. The series connected resistance R = 1/2*X_c=1/(2*pi*f_{res}*C)≈6Ω. Due to RC less than hT, the time constant τ is still the same to above.

For active control method, There is one additional capacitor current control loop. The transfer function is:

$$W(s) = \frac{K_{pwm}}{(Ts+1)(L_1Cs^2+RCs+1)} \tag{7}$$

Where the L_1*C is too small and can be ignored. Through similar way we can calculate that K_{pc}=5. The topologies is given in figure 5, figure 6, figure 7, and figure 8.

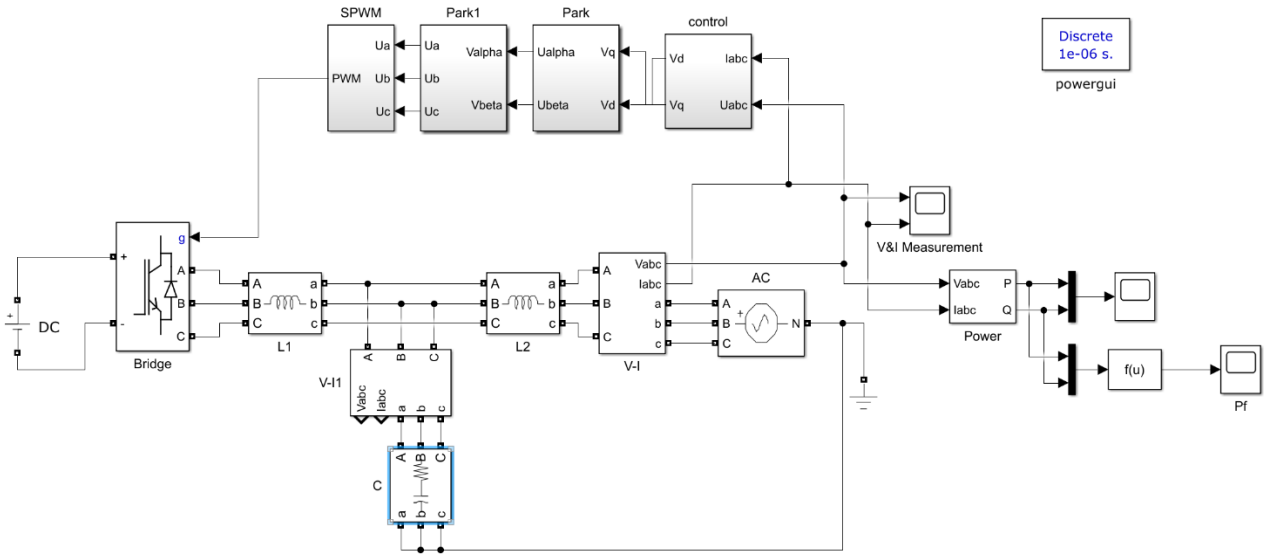


Fig. 5 Main circuit of LCL filter with passive damping control system (Photo/Picture credit: Original)

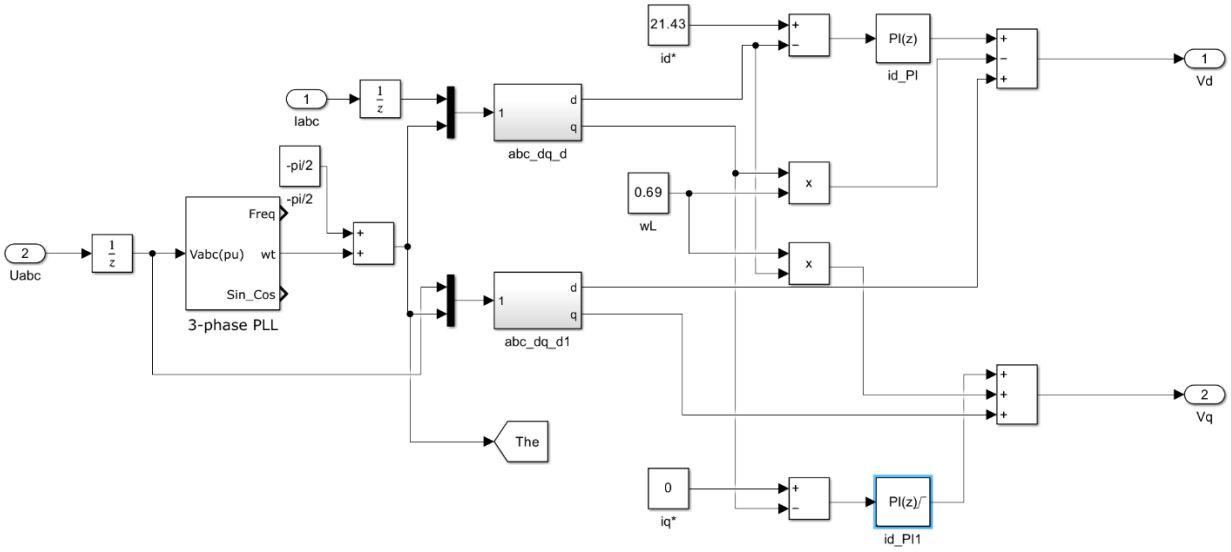


Fig. 6 Control logic display of passive damping control system (Photo/Picture credit: Original)

For the active damping control system there is only one additional proportional controller loop of capacitor current, and the resistance shown in RC block is only 1nΩ.

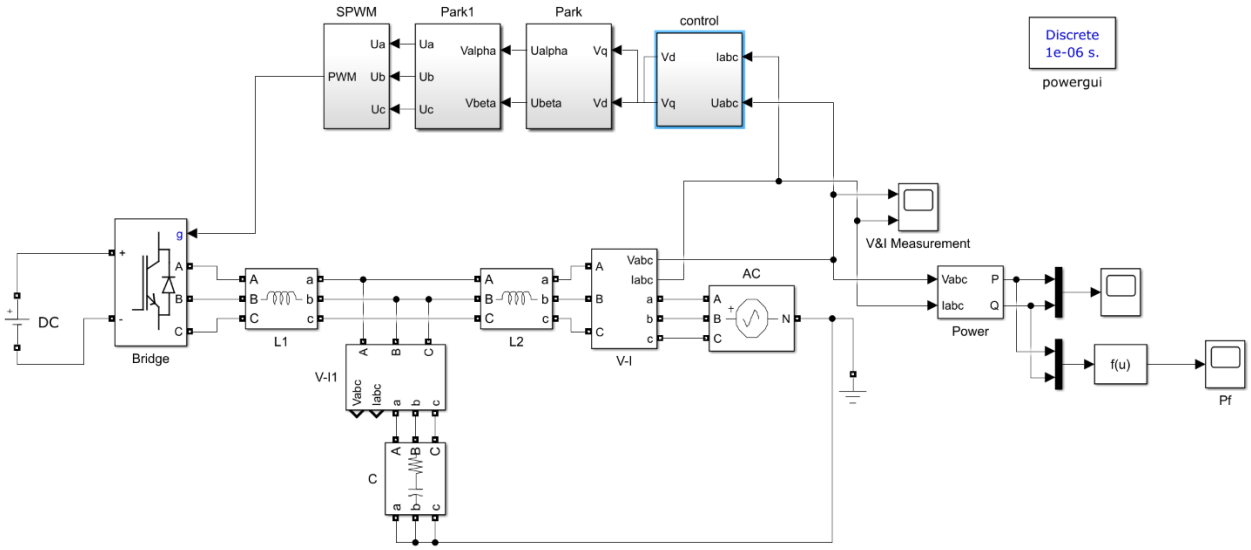


Fig. 7 Control logic of active damping control system (Photo/Picture credit: Original)

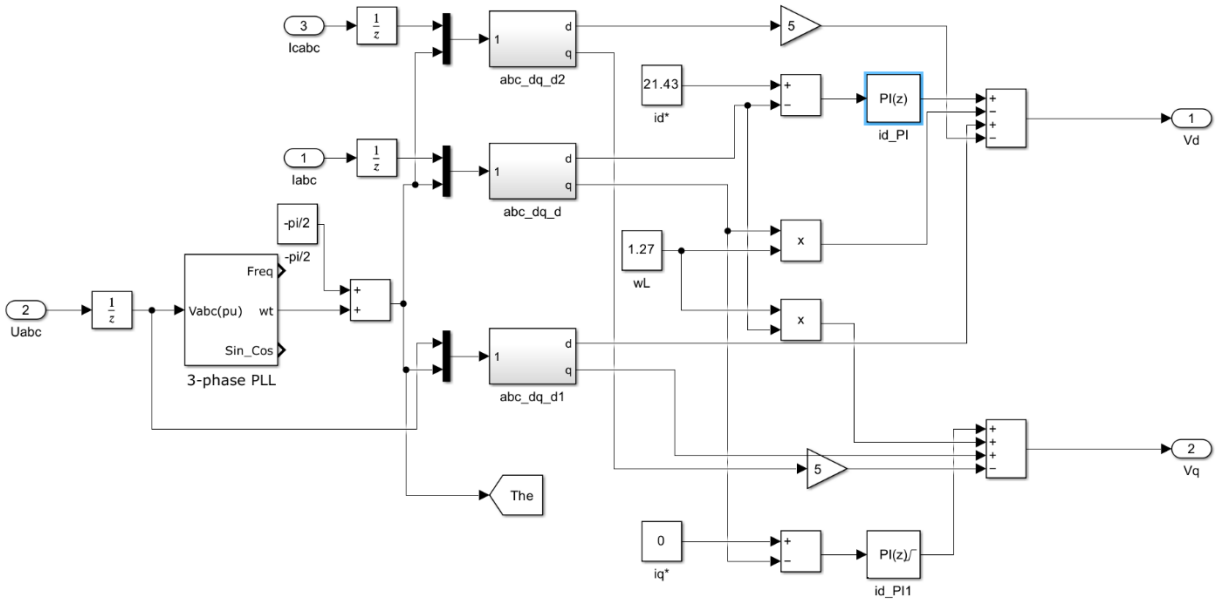


Fig. 8 Control logic display of active damping control system (Photo/Picture credit: Original)

The comparation of output voltage and current based on two different control strategies are shown in figure 9 and figure 10.

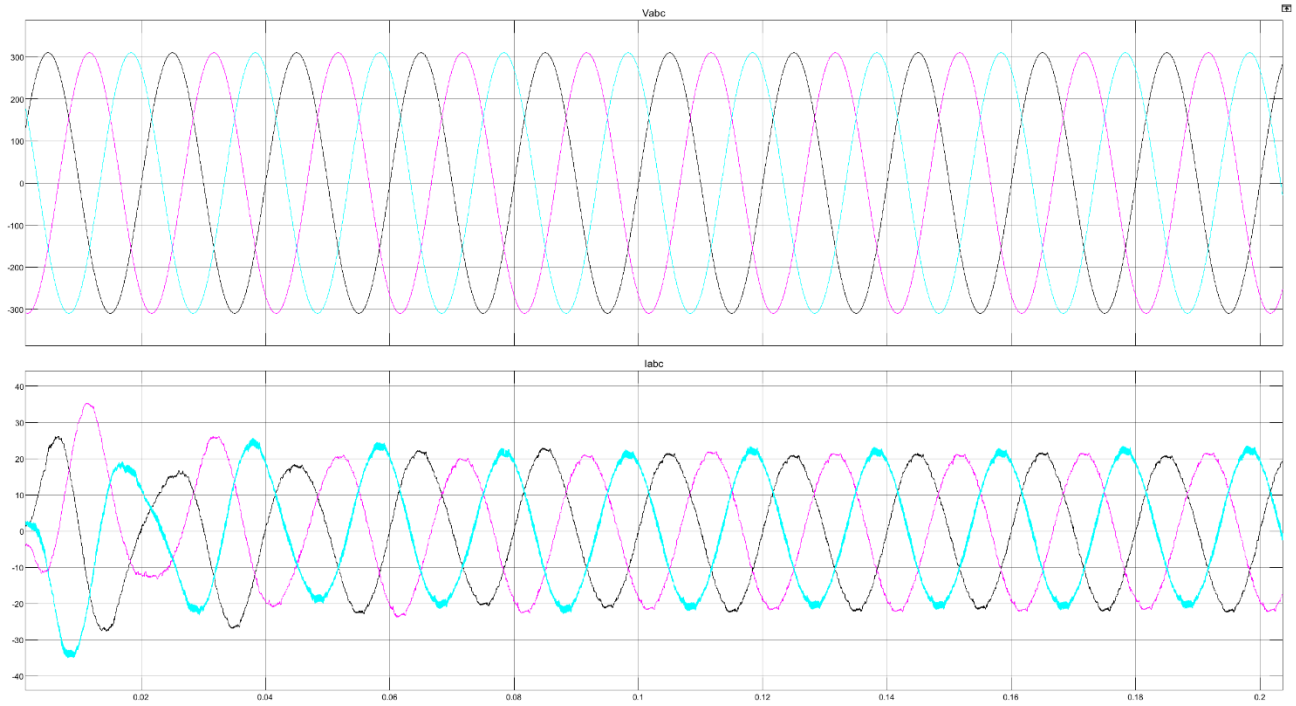


Fig. 9 Output voltage and current waveform of passive damping control system (Photo/Picture credit: Original)

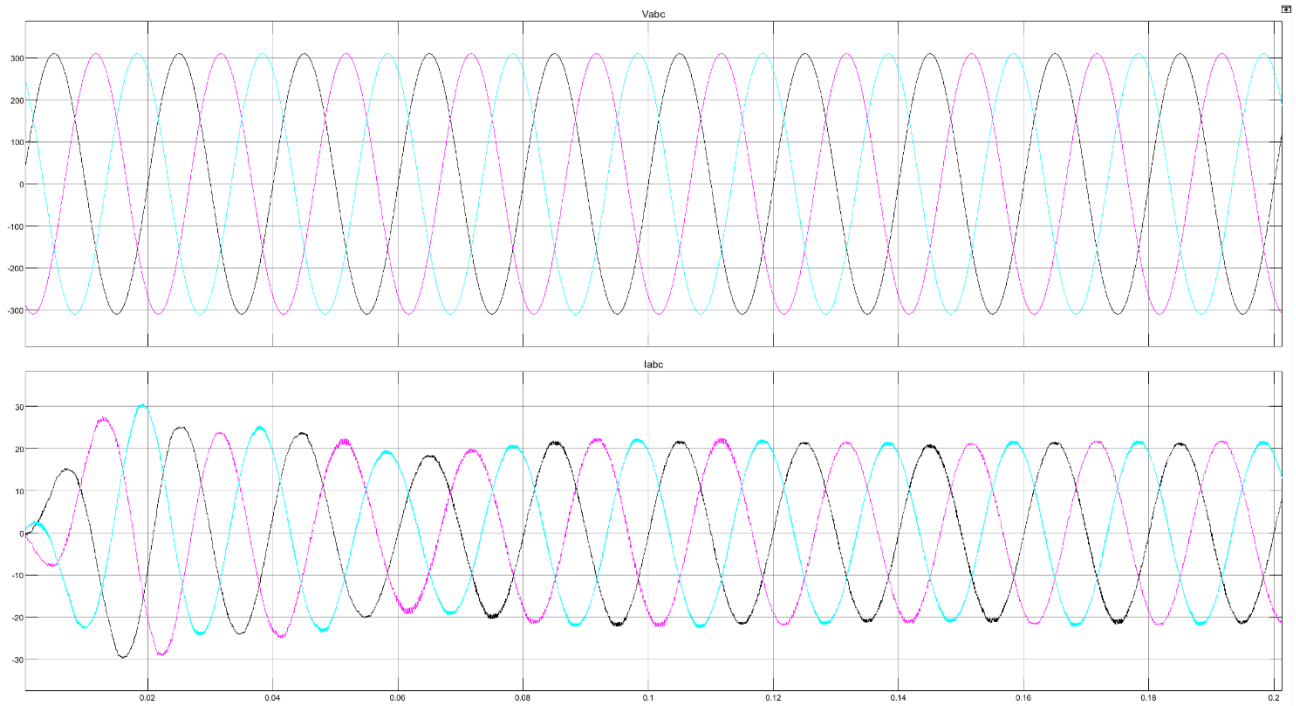


Fig. 10 Output voltage and current waveform of active damping control system (Photo/Picture credit: Original)

Compare with figure 9 and figure 10, for the initial regulating process, the passive control strategy behaves oscillation with higher amplitude, while the active control strategy behaves longer response time. For both control strategies, the voltage and current are all sinusoidal waves with basically the same phase, achieving unit power factor grid connection. From the figure 9 and figure 10, we can also find the current amplitude both stabilize near the set value (21.43A).

Till to the FFT analysis of output current of two control strategies, the total harmonic distortion of passive is 1.92% and active is 1.91%. only a little bit higher than passive (analysis sampled from waveform in stable stage).

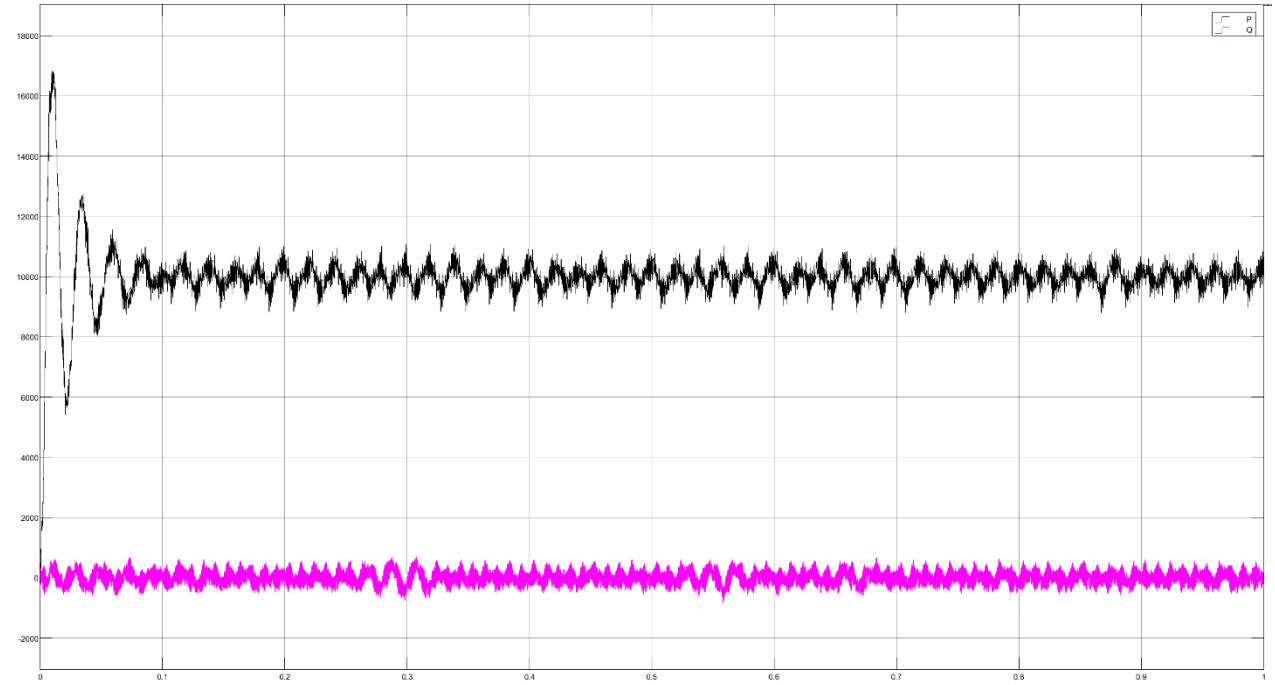


Fig. 11 Active(black) and reactive power(magenta) waveform of passive damping control system (Photo/Picture credit: Original)

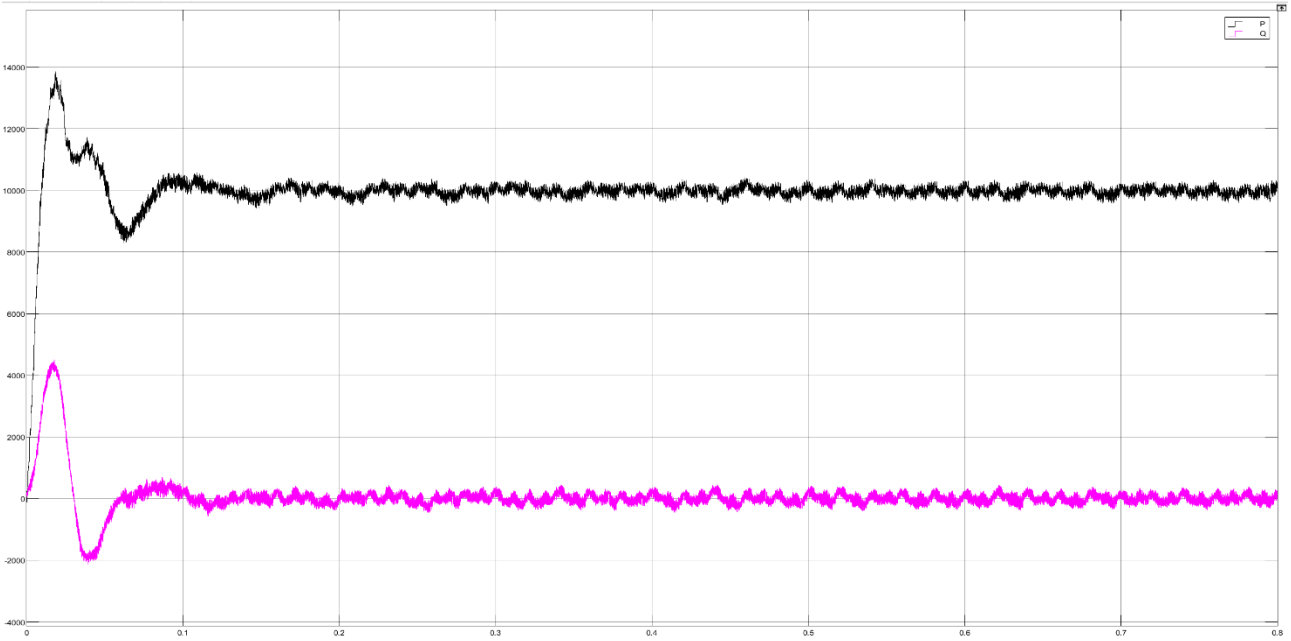


Fig. 12 Active(black) and reactive(magenta) power waveform of active damping control system (Photo/Picture credit: Original)

From figure 11 and figure 12, both control strategies' P, Q stabilized near the set value (10kW; 0var). The passive waveform behaves a distinct oscillation. In practical applications, it's better to add a limitation with differential controller block. For the active controller strategy, there is longer response time for both P and Q. means the proportional coefficient directly calculated needs further adjustment.

To sum up, both active damping and passive damping controller strategies can maintain stable operation. Passive damping series resistors will increase losses and reduce the efficiency of the circuit, while active damping can avoid additional losses and require more sensors [10].

5. Summary

As a major link in the implementation of V2G projects, grid-connected inverter technology is particularly important to provide power quality that meets grid acceptance standards. This paper ravel out the design of LCL filter's parameters. Modelling and analyzing the transfer function. On this basis, the mathematical model of control system is concluded. In virtue of MATLAB Simulink configuration, the simulation of theory model is prepared. Comparing with the simulation results, under the same conditions, the passive damping method based on single-loop control has been confirmed that the output current THD level is not much different from the active damping method based on double-closed-loop control, but the inertia of the active power is larger and the oscillation is more obvious.

The grid-connected inverter topology and control strategy proposed in this article provide a reliable inversion strategy for the stable DC voltage source of electric vehicle batteries. The converted electric energy has lower THD (in compliance with IEEE standards) and a relatively stable power factor. If higher filtering efficiency is pursued, the LLCL filter mentioned is referentially valuable.

The response times of both control strategies are around 0.1s, and there is still room for improvement in system stability and dynamics. In engineering applications, appropriately increasing the proportional parameter kp and reducing the integral parameter ki can achieve faster response time and improve the system dynamic performance. For the inertial oscillation part, it is also worth to try to add differential control.

References

[1] Harb A, Hamdan M. Power quality and stability impacts of Vehicle to grid (V2G) connection. 2017 8th International Renewable Energy Congress (IREC). IEEE, 2017: 1-6.

[2] Sovacool B K, Noel L, Axsen J, et al. The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review. Environmental Research Letters, 2018, 13(1): 013001.

[3] Nguyen N, Mitra J. An analysis of the effects and dependency of wind power penetration on system frequency regulation. IEEE Transactions on Sustainable Energy, 2015, 7(1): 354-363.

[4] Liu F, Zha X, Zhou Y, et al. Design and research on parameter of LCL filter in three-phase grid-connected inverter. 2009 IEEE 6th International Power Electronics and Motion Control Conference. IEEE, 2009: 2174-2177.

[5] Xu Jinming, Xie Shaojun, Huang Ruhai. Robust Current control of LCL Filter grid-connected Inverter. Automation of Electric Power Systems, 2012, 36(19): 99-104.

[6] Guo Xiaoqiang, Wu Weiyang, Gu Herong, et al. Modeling and Stability Analysis of Direct Output Current Control in LCL Interface of Grid-connected Inverter. Transactions of China Electrotechnical Society, 2010, 25(3): 102-109.

[7] Xue M Y. Decoupled control and optimized design of grid-connected inverter with LCL filter. Huazhong University of Science & Technology, Wuhan, China, 2012.

[8] Zhao C, Hu Y, Luan K, et al. Energy storage requirements optimization of full-bridge MMC with third-order harmonic voltage injection. IEEE Transactions on Power Electronics, 2019, 34(12): 11661-11678.

[9] Wu R, Dewan S B, Slemon G R. Analysis of an ac-to-dc voltage source converter using PWM with phase and amplitude control. IEEE Transactions on industry Applications, 1991, 27(2): 355-364..

[10] Hudson R M, Thorne T, Mekanik F, et al. Implementation and testing of anti-islanding algorithms for IEEE 929-2000 compliance of single-phase photovoltaic inverters. Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002. IEEE, 2002: 1414-1419.