Power Control of Single Phase Active Rectifier

A. KARAFIL and H. OZBAY

Abstract—**The most important feature of active rectifier circuits is the ability to adjust the power factor and DC bus voltage, when compared to diode rectifiers. However, odd current harmonics occur in the grid since hard switching state occurs in the active rectifier circuit. A filter should be used on the grid side to reduce the current harmonics. Although there are many types of filters, one of the most suitable filter types is LCL filter when considering the factors such as cost and size. In this study, LCL filter design calculation is performed and PSIM simulation results of active-reactive power controlled LCL filter proportional resonant (PR) current controlled single phase active rectifier circuit is given. The system is designed according to the active power of 600 W. Then, by adding reactive power to the system, it is proved that the power control is carried out successfully.**

Index Terms— **LCL filter, Power control, PR current controller, Single phase active rectifier.**

I. INTRODUCTION

THE SINGLE phase rectifier circuits are used in many industrial applications requiring DC bus voltage such as electrical railway transportation [1], [2], uninterruptible power supply [3], electrical vehicle charger [4], micro turbine generator units [5] and renewable energy applications as wind energy [6]. While the control of power factor and dc bus voltage is an important advantage in active rectifiers, the increase of switching losses and current harmonics occurring due to hard switching are the disadvantages of this system. A filter should be used on grid side in order to decrease the high order current harmonics. In the advance power electronics technology it is desirable to have small and light circuit sizes. One of the circuit elements that increases the size of the circuit is the filter. For this purpose, the filter used in the system should be effective, light and with small size. The LCL filter is one of the most suitable filter types considering the reduction of harmonics, cost and size [7-10].

In the case of single phase active rectifier circuits, it is necessary to perform current and power control so that the DC voltage can be adjusted and the power factor can be controlled. Many control methods are used in current and power control [11], [12] such as model predictive [12], hysteresis [13], proportional integral (PI) [14], proportional resonant (PR) [15], repetitive [16], sliding mode [17], fuzzy neural [18]. PI and PR, which are among the linear control techniques, are the most widely used controllers. Although other control techniques show a good dynamic response, they create a time delay in the system [19].

In order to ensure synchronization with the grid in active rectifier circuits, phase locked loop (PLL) is required. The PLL algorithm provides control of the grid frequency. Many PLL algorithms are used in active rectifier circuits. T/4 delay PLL is one of the easy algorithms for obtaining the phase angle in single phase applications [20].

In this study, an analysis of the active-reactive power controlled LCL filter PR current controlled single phase active rectifier circuit was conducted and the simulation results were given. T/4 delay PLL was used as PLL algorithm. System was firstly tested without reactive power control and then reactive power was added and active and reactive power controlled simulation results were obtained.

This paper is organized as follows: Section II presents the PLL structured used by calculating the LCL filter parameters. In section III, power control and PR current control technique used in the system are introduced. Section IV gives the simulation results. In the conclusion part, the simulation results are interpreted.

II. DESIGN OF SINGLE PHASE ACTIVE RECTIFIER BASED LCL FILTER

A. Determination of the LCL Filter Values

The connection diagram of the designed LCL filter single phase active rectifier circuit is shown in Fig.1.

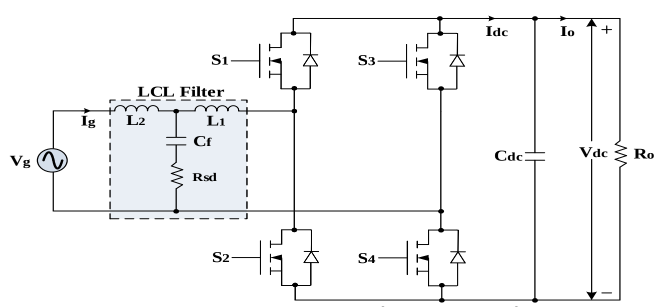

Fig.1. Single phase active rectifier based LCL filter

Before determining LCL filter parameters, it is necessary to determine the parameters of the single phase active rectifier circuit. Table 1 presents the parameter values to be used in the system.

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Manuscript received December 26, 2018; accepted July 6, 2019.
DOI: 10.17694/bajece.503207

TABLE I
PARAMETER VALUES REQUIRED FOR RECTIFIER CIRCUIT

Parameters of Rectifier	
Parameter	**Value**
Grid Voltage (V_g)	220 V
Output Power of Rectifier (P_n)	600 W
DC Bus Voltage (V_{DC})	400 V
Grid Frequency (f)	50 Hz
Switching Frequency (f_{sw})	10 kHz

The inductor (L_1) value on the converter side is calculated by the following equations.

$$\Delta I_{L-\max} = a.\frac{P_n\sqrt{2}}{V_g} \tag{1}$$

$$L_1 = \frac{V_{DC}}{16.f_{sw}.\Delta I_{L-\max}} \tag{2}$$

Where "*a*" is the current ripple ratio. Impedance and capacitor values of the circuit are calculated as follows:

$$Z_b = \frac{V_g^2}{P_n} \tag{3}$$

$$C_b = \frac{1}{2\pi f.Z_b} \tag{4}$$

When determining the value of the filter capacitor, 5 % of the ideal C_b value is taken. However, a factor (k) greater than 5 % can be preferred.

$$C_f = k.C_b \tag{5}$$

There is a relationship between the grid and the inductors on the converter side when determining the inductor value (L_2) on the grid side. This relationship is indicated by "*r*" coefficient and in the range of $0< r \leq 1$. Therefore, the L_2 value is calculated by the following equation [21], [22].

$$L_2 = r.L_1 \tag{6}$$

By the equations, it was calculated that L_1=3.24 mH, C_f=7.892 µF and L_2=0.972 mH. Once the LCL filter parameters are determined, the resonance frequency can be calculated as follows:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1.L_2.C_f}} \tag{7}$$

Moreover, the resonance frequency (f_{res}) should be within the ranges shown in Equation (8) [22].

$$10f < f_{res} < 0.5 f_{sw} \tag{8}$$

A series resistor is connected to the capacitor in order to reduce the oscillations and prevent the filter from unstable state. This resistor is called as "damping resistor" and is calculated by the following equation.

$$R_{sd} \geq \frac{1}{3.\omega_{res}.C_f} \tag{9}$$

B. PLL Structure

The control of the grid frequency is performed by the PLL algorithm. In this study, T/4 delay PLL algorithm is used. T/4 delay PLL algorithm needs α-β and d-q reference frames. In order to obtain the orthogonal imaginary signal (β component), α component must be shifted as π/2. Between them α component is in the real and the β component is in the imaginary axis. Equation (10) was used to transform the α-β into d-q axis frame with Park Transform in the T/4 delay PLL circuit [20]. Fig.2 shows the α-β transform and T/4 delay PLL structure.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{10}$$

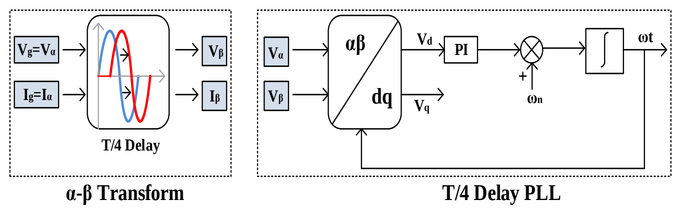

Fig.2. The block diagram of α-β Transform and T/4 delay PLL structure

III. Power Control And PR Current Control Technique

The control block diagram of the system is shown in Fig.3.

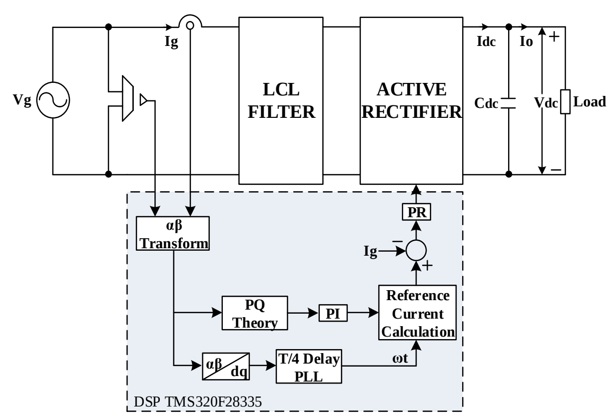

Fig.3. The control block diagram of the single phase active rectifier

Active-reactive power (PQ theory) calculation was conducted by the following equations.

$$P = \frac{1}{2}(V_\alpha.I_\alpha + V_\beta.I_\beta) \tag{11}$$

$$Q = -\frac{1}{2}\left(V_\alpha.I_\beta + V_\beta.I_\alpha\right) \tag{12}$$

 ISSN: 2147-284X http://dergipark.gov.tr/bajece

The obtained power error values are passed through the PI controller and added to the ωt formula obtained by PLL algorithm and therefore the reference current is calculated. The reference current formula is found using the following equations: [12], [23].

$$\theta = \tan^{-1}\left(\frac{Q_{ref}}{P_{ref}}\right) \tag{13}$$

$$I_g = \frac{P_{ref}}{V_q.\cos\theta} \tag{14}$$

$$i_{ref} = \sqrt{2}.I_g.\sin(\omega t - \theta) \tag{15}$$

The obtained reference current is subtracted from the I_g (I_α) current value to obtain the error current. The error current is passed through the PR current controller to generate the switching signals.

PR controller is one of the control methods used in single or three phase systems connected to the grid. PI and PR are controllers that are similar to each other and have many common points. The PR controller is generally preferred to obtain a zero steady-state error in the control of grid-connected systems. There are some problems in the implementation of the PR controller. In ideal PR controller, unlimited gain harmonics components increase. The formula for the non-ideal PR controller used to reduce the harmonic components is given in Equation (16).

$$G_{nipr}(s) = K_p + \frac{2K_i\omega_c s}{s^2 + 2\omega_c s + \omega_n^2} \tag{16}$$

Where, ω_n is the angular frequency of the grid and the K_p and K_i values are proportional and integral gain values, respectively. ω_c is the cut-off frequency. Non-ideal PR controller has lower gain and band range [24-26].

IV. Simulation Results

The simulation screen image of a single phase active rectifier circuit was given in Fig.4. In the circuit the parameters were determined as follows: R_o=266 Ω, damping resistor R_{sd}=5 Ω and DC capacitor value C_{dc}=470 µF.

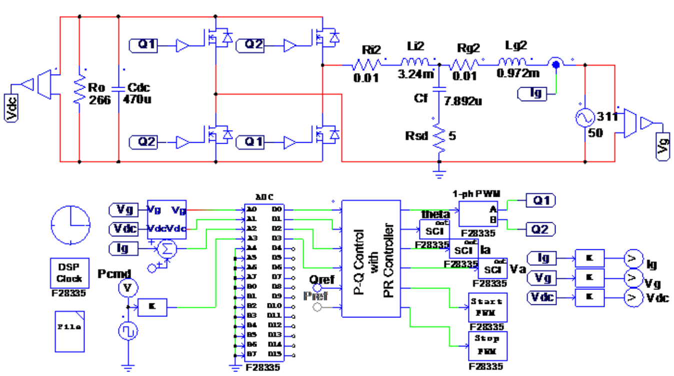

Fig.4. The simulation of the single phase active rectifier circuit

Grid voltage is detected by PLL algorithm and zero transition points are caught and the angular velocity values synchronized with the grid for each period are produced. The grid voltage and the angular velocity values produced as synchronized are shown in Fig.5.

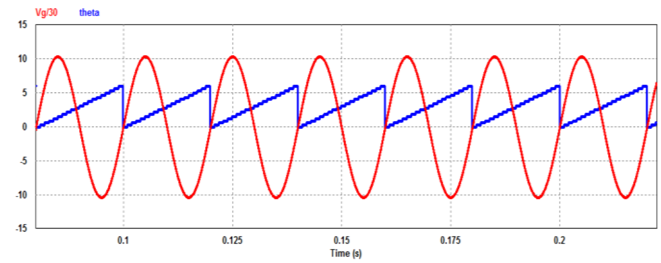

Fig.5. The production of angular speed values by PLL

When the active power of the system is P=400 W and the reactive power is Q=0 VAr, the current and the voltage wave forms of the circuit was shown in Fig.6.

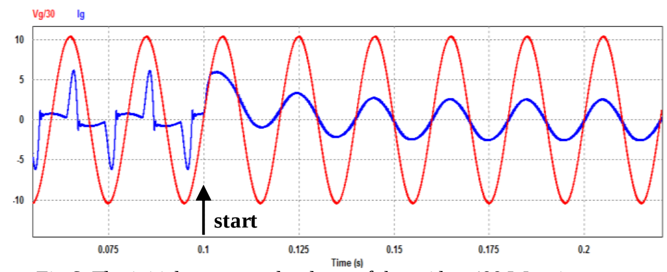

Fig.6. The initial current and voltage of the grid at 400 W active power

The current and voltage waveforms of the grid when the active power was increased from 400 W to 600 were given in Fig.7.

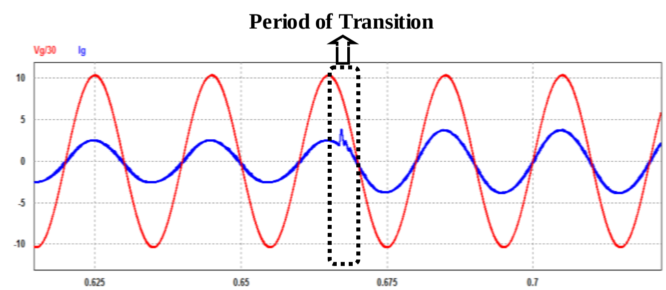

Fig.7. The period of transition from 400 W to 600 W

When P=400-600 W and Q=0 VAr, DC voltage change on the load was shown in Fig.8.

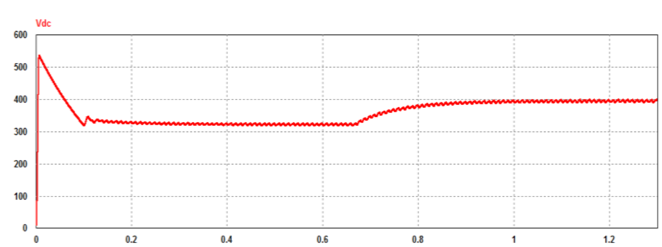

Fig.8. DC bus voltage changing

When P=600 W and Q=0 VAr, the power factor value was found as 0.99 and shown in Fig.9.

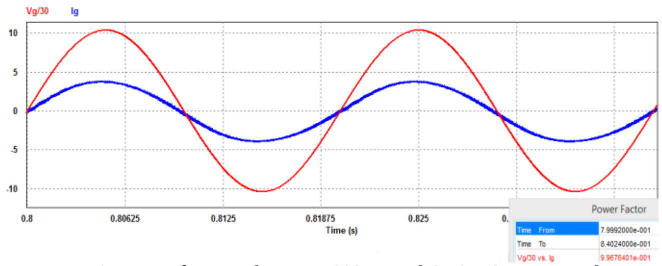

Fig.9. Power factor value at P=600 W and Q=0 VAr power values

The power control of the system was tested by adding reactive power to the system. Current and the voltage wave forms at P=600 W and Q=400 VAr power values were given in Fig.10.

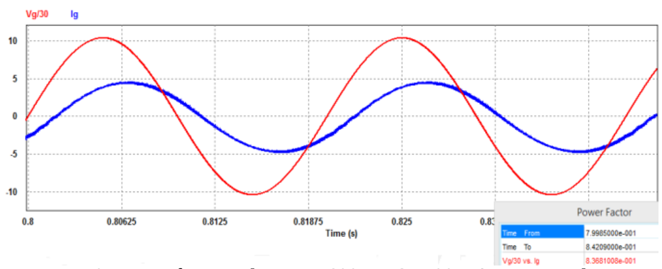

Fig.10. Power factor value at P=600 W, Q=400 VAr power values

At P=600 W and Q=400 VAr power values, power factor was found as 0.83.

Current and the voltage wave forms of the grid at P=600 W and Q=-400 VAr power values were given in Fig.11.

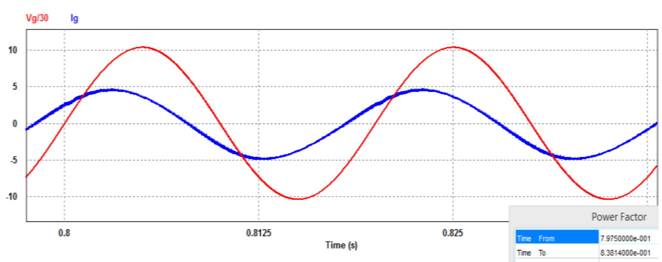

Fig.11. Power factor value at P=600 W, Q=-400 VAr power values

At P=600 W and Q=-400 VAr power values, power factor was found as 0.83.

V. Conclusion

In this study, the active-reactive power control of a LCL filter single phase active rectifier circuit was obtained by the simulation study. PI for power control, PR controller for current control and T/4 delay PLL algorithm for grid frequency control were used. Active power control was performed for P=600 W, Q = 0 VAr system power values and power factor value was found as 0.99. Then, reactive power was added to the system and P=600 W, Q=400 VAr and P=600 W, Q=-400 VAr power values were tested respectively and the power factor was found as 0.83. In this study, active-reactive power control of a single phase active rectifier circuit with LCL filter was performed.

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