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A Closed Loop Control of Quadratic Boost Converter Using PID-controller

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ABSTRACT

This paper presents an implementation of open loop and closed loop control of quadratic boost converter (QBC) using PID-controller. QBC consists of boost converter and fly back converter driven by a single switch. QBC is designed especially for regulating the DC interface between various micro sources and DC-AC inverter to electricity grid. QBC, P, PI and PID-controller are modeled, compared and evaluated by MATLAB simulation. It has been found that the transient and steady state performance is improved using PID-controller. This converter achieves high step-up voltage gain with appropriate duty ratio and low voltage stress on the power switch. The simulated open loop and closed loop performance is verified experimentally.

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1. INTRODUCTION

Renewable energy includes solar energy, wind energy and fuel cells, etc. These energy sources are renewable and utilization of these energy sources creates zero or little emissions [1]. Renewable energy is becoming increasingly important and prevalent in distribution systems, which provide different choices to electricity consumers whether they receive power from the main electricity source or in forming a micro source not only to fulfill their own demand but alternatively to be a power producer supplying a micro grid [2-5]. Also distributed generation (DG) systems using renewable energy increase the reliability.

Now renewable energy systems are relatively expensive and hence the cost is higher than the fossil fuel [6-8]. So renewable energy sources capture a small share of the total energy market. However, with the development of technology, the cost of renewable energy is decreasing steadily and it will become more cost effective than fossil fuel in the future technology; this is the key to increase the market share of renewable energy power generation. For renewable energy systems, power electronic play a vital role [9-12]. Sometimes they are the most expensive part of the system. Reducing cost, increasing efficiency and improving reliability of power electronics and electric machines are the technical challenges facing wider implementation of renewable energy power generation. Renewable energy sources derive their energy from existing flow of energy, from on-going natural processes such as sun, wind, flowing water and geothermal heat flows [13-18]. The most feasible alternative energy sources include solar, fuel cell and wind.

In conventional boost converter the voltage gain is not enough to convert to a suitable AC source as a model micro-source [18-22]. The efficiency and voltage gain of conventional boost converter are restrained by either the parasitic effect of the power switches or the reverse recovery problem [23-28]. The diode reverse recovery problem increases the conduction losses, degrade the efficiency and limit the power level of conventional boost converter [29-33]. To overcome these problems, QBC has been proposed to interface with renewable energy sources [34-37].

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2.OPERATING PRINCIPLE OF QUADRATIC BOOST CONVERTER

QBC is mainly used in renewable energy system. It is the combination of boost converter and flyback converter.These two segments are named as first boost stage and second boost stage.This combination is developed to carry out high step-up voltage gain using coupled inductor technique. The proposed converter is a quadratic boost converter with the coupled inductor in the second boost stage. The circuit diagram of QBC is shown in Figure1.

The first boost stage is like a boost converter that includes an input inductor L_{in}, two diodes D_1 and D_2, and a pumping capacitor C_1.The second boost stage is a boost-flyback converter that includes a dual-winding coupled inductor T_1 , two diodes D_3 and D_4 ,and two output capacitors C_{O1} and C_{O2}.The simplified circuit diagram of QBC is shown in Figure 2.

In particular, these two stages are driven by a single switch S_1 . The features of this converter are as follows: The quadratic boost converter is effectively extended to a voltage conversion ratio and the first boost stage is benefited by input current ripple reduction. The leakage inductor energy of the coupled inductor can be recycled, which reduces the voltage stress on the active switch.

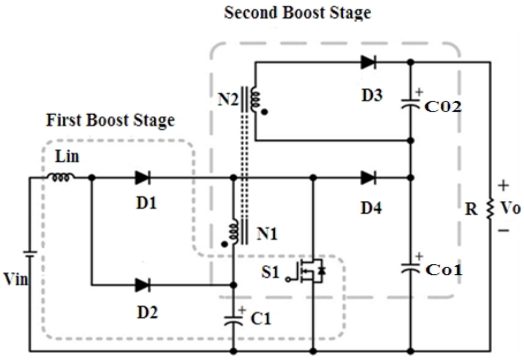

Figure 1. Circuit diagram of QBC

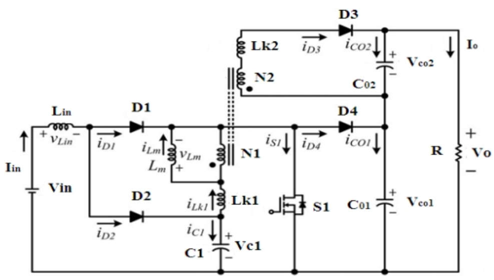

Figure 2. Simplified circuit diagram of QBC

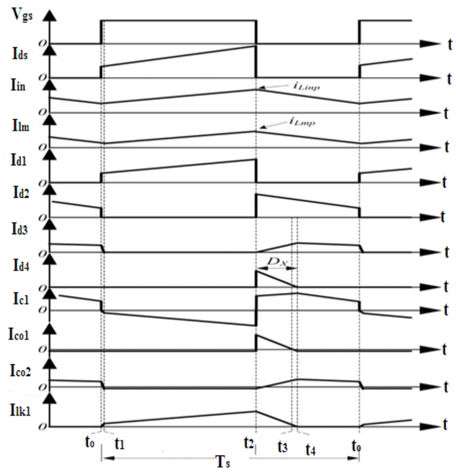

Figure 3. Typical waveforms of the QBC, both L_m and L_{in} in CCM operation.

The dual-winding coupled inductor consisted of a magnetizing inductor L_m, primary leakage inductor L_{k1} , secondary leakage inductor L_{k2} , and an ideal transformer, which constituted the primary and secondary windings, N_1 and N_2. Figure 3 shows several typical waveforms of QBC during their operating modes at one switching period T_S while both the input inductor L_{in} and the magnetizing inductor L_m are operated in continuous conduction mode.

QBC achieves high step-up voltage gain using the coupled inductor technique. QBC has improved performance characteristics such as higher power capability, modularity and improved reliability. QBC operates at appropriate duty ratio and low voltage stress on the power switch. Additionally, the energy stored in the leakage inductor of the coupled inductor can be recycled to the output capacitor.

3. STEADY-STATE ANALYSIS OF QUADRATIC BOOST CONVERTER

The QBC is operated in five different modes. The time duration of Mode I and IV are transition periods, only Modes II, III, and V are considered at CCM operation for the steady-state analysis. During the time duration of Mode II, the main switch S_1 is conducted and the coupling coefficient of the coupled inductor k is considered as $L_m/ (L_m+L_{k1})$.

The following equations can be written as:

$$vL_{in}= V_{in} \tag{1}$$

$$vL_m= L_m/L_m + L_{k1}V_{C1} = kV_{C1} \tag{2}$$

$$vL_{k1} = V_{C1} - V_{Lm}= (1 - k)V_{C1} \tag{3}$$

$vL_{k2} = n \cdot vL_m$. (4)

During the period of Modes III and V that main switch S_1 is turned OFF, the following equations can be found as:

$vL_{in} = V_{in} - V_{C1}$ (5)

$vL_m = V_{C1} - V_{CO1} - V_{Lk1}$ (6)

$vL_{k2} = -nvL_m - V_{Co2}$ (7)

where the turn ratio of the coupled-inductor n is equal to N_2/N_1. The voltage across inductor L_{in} by the volt-second balance principle is shown as:

$V_{C1} = 1/1 - DV_{in}$. (8)

thus V_{Co1} and V_{Co2} can be obtained from the following equations:

$V_{Co1} = 1 - D + kD/1 - DV_{C1} - V_{Lk1}$ (9)

$= 1 - D + kD/(1 - D)2\ V_{in} - V_{Lk1}$ (10)

$V_{Co2} = nkD/1 - DV_{C1} - V_{Lk2}$ (11)

$= nkD/(1 - D)2\ V_{in} - nV_{Lk1}$ (12)

The output voltage V_o can be expressed as:

$V_O = V_{Co1} + V_{Co2}$. (13)

By substituting Equations (3), (11), and (12) into Equations (13), we can obtain the voltage gain M_{CCM}

$M_{CCM} = V_O/V_{in} = k(n + 1) + n(D - 1)/(1 - D)2$ (14)

By substituting $k = 1$ into Equations (14) and (12), the input-output voltage gain can be simplified as:

$M_{CCM} = V_O/V_{in} = 1 + nD/(1 - D)2$ (15)

$M_{CCM}\text{-}T_1 = V_{Co2}/V_{C1} = nD/1 - D$ (16)

The duty ratio of the QBC is larger than 0.55, the voltage gain is higher than the converters in other works [16, 18, 19].

In CCM operating modes, the voltage stresses on S_1 and D_1-D_4 are given as:

$V_{ds} = V_{D4} = V_o/1 + nD$ (17)

$V_{d1} = D_{vo}/1 + nD$ (18)

$V_{d2} = (1 - D)V_o/1 + nD$ (19)

$V_{d3} = nV_o/1 + nD$ (20)

4. SIMULATION RESULTS

4. 1. Quadratic Boost Converter With Single Switch

The QBC consists of boost converter and fly back converter driven by a single switch. QBC is simulated with P, PI and PID-controller using MATLAB simulink and the results are presented. Scope is connected to display the output voltage. QBC is simulated in both open and closed loop systems.

The following values are found to be a near optimum for the design specifications:

TABLE 1. Simulation parameters

Parameter	Rating
Input voltage	48V
Input inductor L_{in}	29 µH
Magnetizing inductor L_m	94µH
Co1= Co2	220µF
C1	1000 µF
Lk1=Lk2	500 µH
Switching Frequency	40kHz
Diode	IN 4007
MOSFET	IRF840
R	200Ω

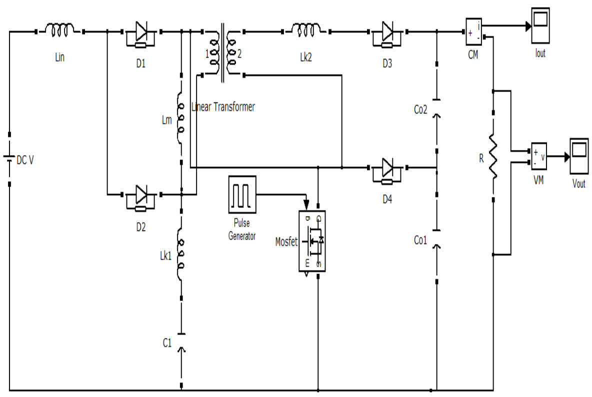

Figure 4. Simulated diagram of QBC with single switch

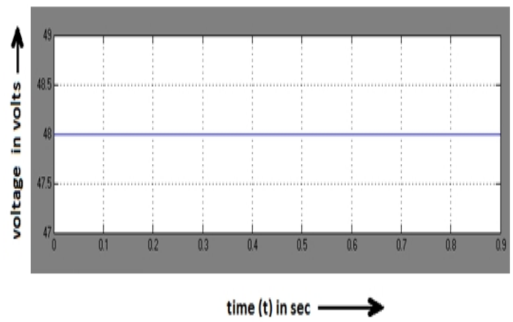

Figure 5. Input voltage

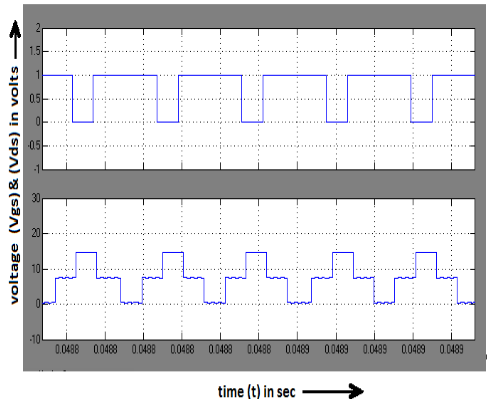

Figure 6. MOSFET gate pulse and drain to source voltage waveform (Vgs & Vds)

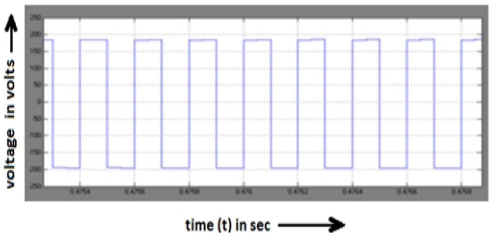

Figure 7. Transformer output voltage

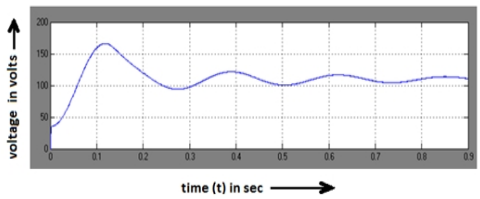

Figure 8. Output voltage

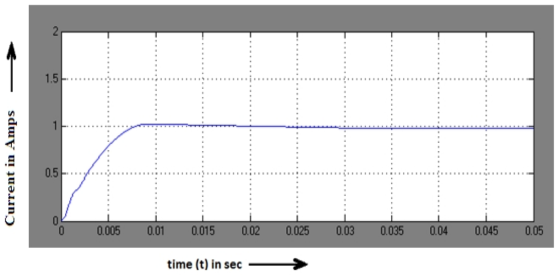

Figure 9. Output current

4. 2. Open Loop System Open loop QBC is simulated using MATLAB simulink. In open loop system output can be varied by varying the input and the corresponding output voltage is measured. Figure 10 shows the open loop QBC.

In open loop system the input voltage increases after some time delay.This gives an error voltage which in turn increases the output voltage. Gain cannot be easily controlled because there is no feedback in open loop system.

4. 3. Closed Loop System Closed loop system is established to achieve a regulated output.The closed loop QBC is simulated with P, PI and PID-controller using MATLAB simulink and the results are presented. The output voltage is continuously compared to check its variation with the reference voltage using a differential amplifier. The differential signal is amplified and fed to a comparator circuit which compares it with a triangular wave. The comparator output is fed to the MOSFET switch. Another triangular wave which is phase shifted by 180 degree is compared with the same differential amplifier output and in turn of the comparator output. The signals are fed as the pulse signals to the MOSFET switch which in turn regulates the output voltage. The error signal is applied to the controller, the output of the controller is given to the gate of MOSFET.

4. 3. 1. Closed loop QBC with P-controller Closed loop QBC with P-controller simulated using MATLAB simulink as shown in Figure 10., Figure 11 and 12 depicts the output voltage and current. Here Kp=100.

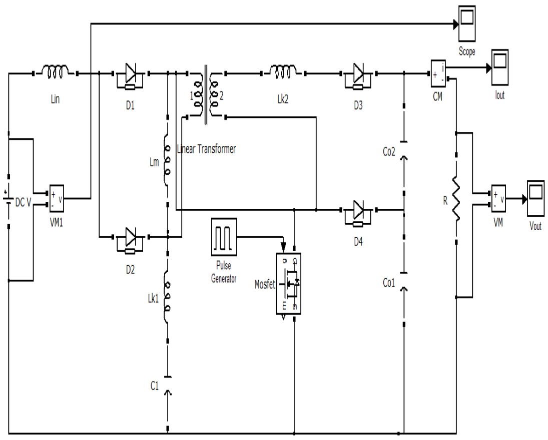

Figure 10. Simulated diagram of open loop QBC

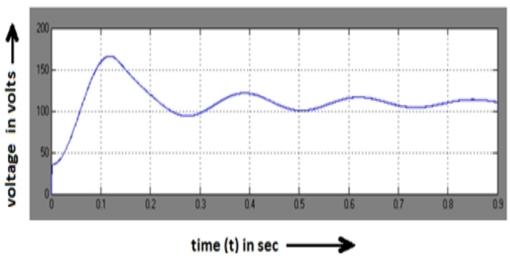

Figure 11. Output voltage

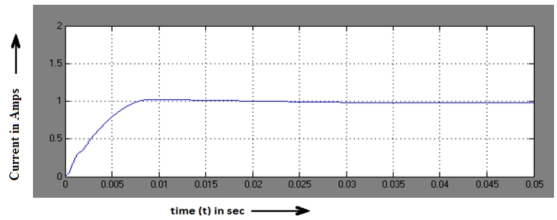

Figure 12. Output current

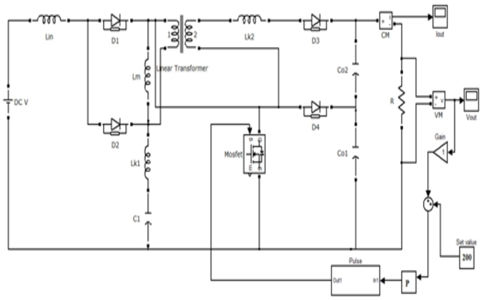

Figure 13. Simulated diagram of closed loop QBC with P-controller.

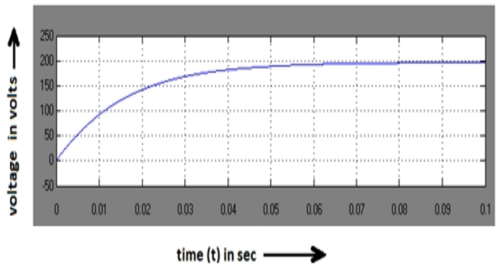

Figure 14. Output voltage

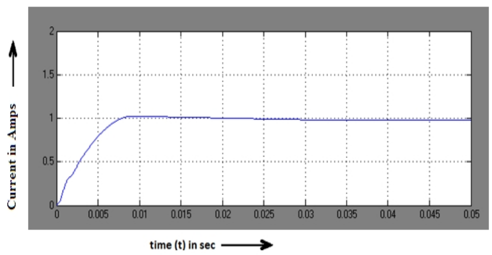

Figure 15. Output current

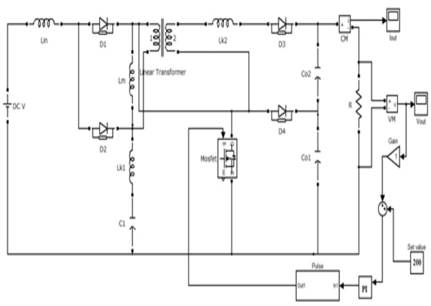

Figure 16. Simulated diagram of closed loop QBC with PI-controller.

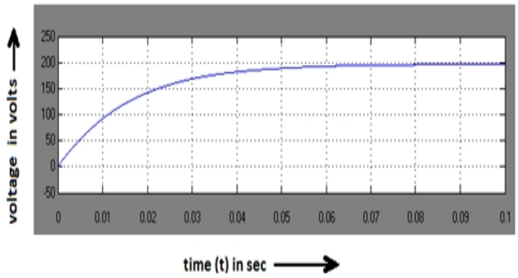

Figure 17. Output voltage

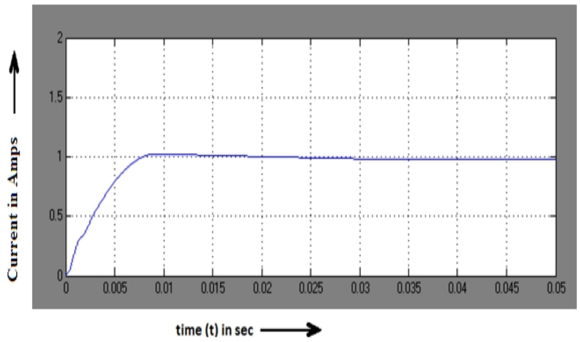

Figure 18. Output current

The performance of QBC using P-controller reaches to a steady state error and lower voltage gain

4. 3. 2. Closed loop QBC with PI-controller Closed loop QBC with PI-controller simulated using MATLAB simulink as shown in Figure13., Figure 14 and 15 depicts the output voltage and current. Here Kp=100 and Ki=100. The performance of QBC using PI-controller reaches to a peak overshoot, slow response and more oscillations.

4. 3. 3. Closed Loop QBC with PID-controller Closed loop QBC with PID-controller is simulated using MATLAB simulink is shown in Figure 16. Figure 17. and 18 depicts the output voltage and current. The tuning of controller parameters is done by Zeigler & Nichols method. Here K_p= 0.1, K_i= 0.2 and K_d= 0.2.

The performance of QBC using PID-controller has no steady state error and low peak overshoot under the load change condition. QBC is improved in terms of transient and steady state response, increases conversion efficiency and reduces the voltage stress on the active switch. PID-controller perform faster switching operation.

4. 4. Performance Comparison Performance comparision has been made between P, PI and PID controlled QBC and results are presented in Table 2.

It clearly shows the improved performance of PID-controller over P and PI-controller in terms of rise time, peak time and peak overshoot. From the comparison results, PID-controller shows less voltage deviation, dynamic performance, fast response and high accuracy.

TABLE 2. Comparison of P, PI and PID-controllers

Simulated results	P-controller	PI-controller	PID-controller
Rise time	0.04 Sec	0.035 Sec	0.03 Sec
Peak time	0.065 Sec	0.063 Sec	0.062 Sec
Settling time	0.087 Sec	0.082 Sec	0.08 Sec
Maximum peak overshoot	16.59%	16.47%	16.31%
Non linearity	0.23Sec	0.25 Sec	0.2 Sec
Input voltage	48 V	48 V	48 V
Output voltage	200 V	200 V	200 V
Output current	1A	1A	1A

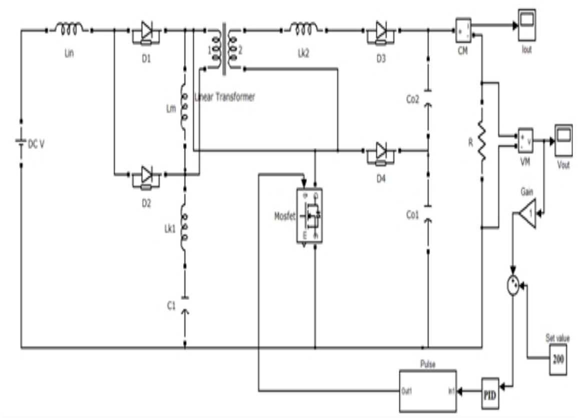

Figure 19. Simulated diagram of closed loop QBC with PID-controller.

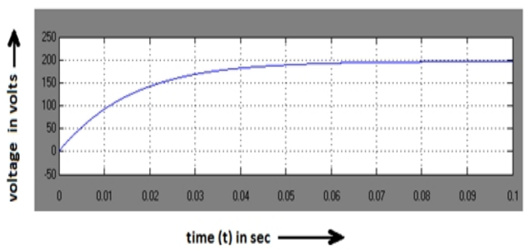

Figure 20. Output voltage

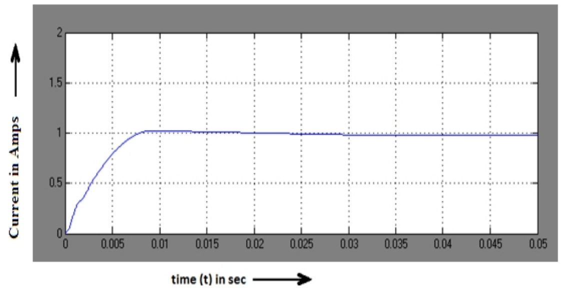

Figure 21. Output voltage

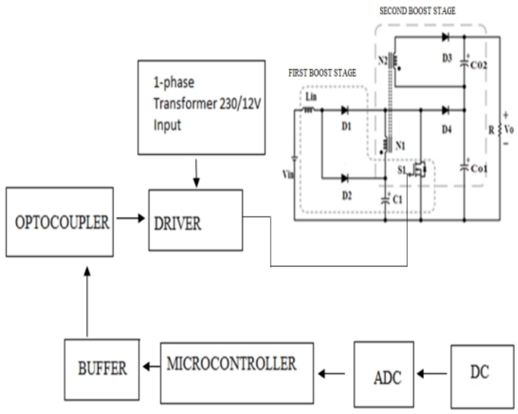

Figure 22. Schematic diagram of QBC

5.EXPERIMENTAL RESULTS

QBC with single switch is developed and tested in the laboratory. 8051 microcontroller has two 16-bit timer/counter registers namely timer 1 and timer 2. Both can be configured to operate either as timers or event counters.

ADC0808 is used for interfacing analog circuit and comparator circuit. To isolate power circuit and control circuit, optocoupler is used. This symmetric PWM output is not capable of driving the MOSFET. Driver is used to amplify the output of the optocoupler and is connected to the gate of the MOSFET.

Figure 23 shows the schematic diagram of QBC with 8051 microcontroller. The following values (see Table 3) are found to be near optimum for the design specifications.

Pulses required for the MOSFET are generated using a ATMEL microcontroller 89C2051.These pulses are amplified using a driver amplifier. The gate pulses are given to the MOSFET of the QBC.

The experimental system is found to be more advantageous and cost effective with microcontroller. QBC has advantages like reduced switching losses, reduced stresses and reduced EMI.

TABLE 3. Hardware parameters

Parameter	**Value**
Capacitor C_1	1000µF
Output capacitor $C_{O1}=C_{O2}$	220µF
Input inductance	500µH
Input voltage	15V
Resistance R	200Ω
MOSFET	IRFP450,10 A,10-500V
Regulator	LM7805, LM7812, 5-24V
Driver IC	IR2110,+500V or +600V
Diode	IN4007
Crystal oscillator	230/15 V, 500mA, 50Hz
Microcontroller	AT89C2051, 2.7V to 6V,0Hz to 24MHz

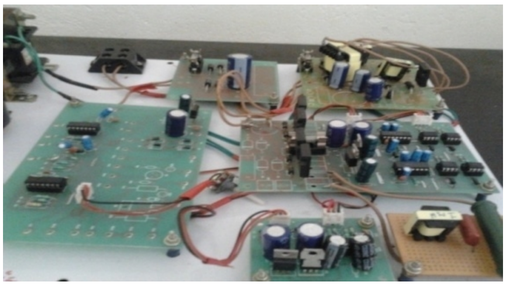

Figure 23. Experimental setup of QBC

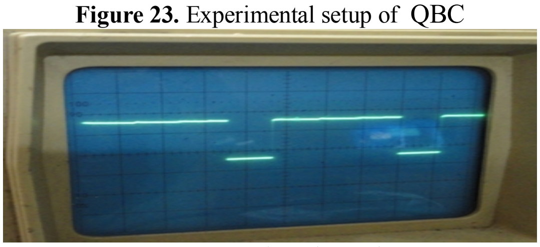

Figure 24. Triggering pulse

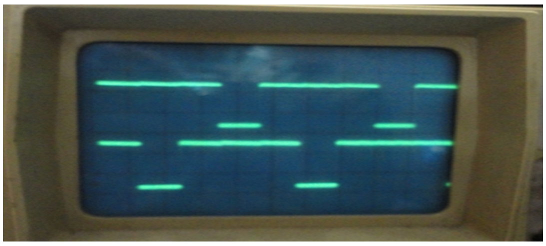

Figure 25. Gate pulse and drain to source voltage (Vgs & Vds)

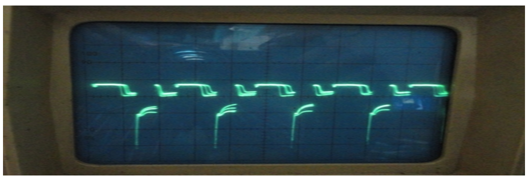

Figure 26. Transformer primary voltage (Vp)

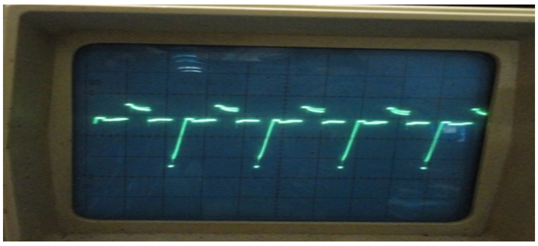

Figure 27. Transformer secondary voltage (Vs)

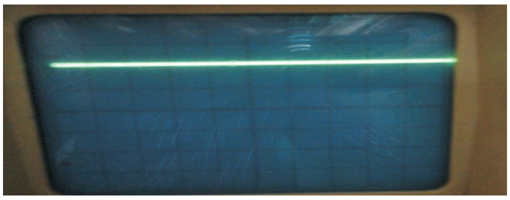

Figure 28. DC Output voltage

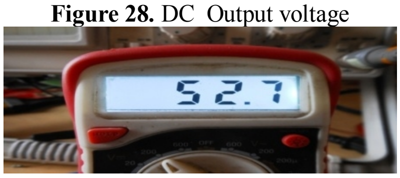

Figure 29. DC Output voltage is measured using multimeter

6.CONCLUSION

The closed loop control of QBC using PID-controller is simulated and implemented. PID-controller is much better in overall performance in terms of rise time, settling time, peaktime and maximum peak overshoot as compared to P and PI-controller. However QBC achieves high step-up voltage with appropriate duty ratio and low voltage stress on the power switch. Additionally the energy stored in the leakage inductor can be recycled to the output capacitor. The use of PID-controller reduces the steady state error, increases the stability with very less oscillations and low overshoot.With all these advantages PID-controller has a potential to improve robustness of QBC. As long as the technology of active snubbed, auxiliary resonant circuit, synchronous rectifiers, or switched-capacitor-based resonant circuits employed in QBC are able to achieve soft switching on the main switch to reach higher efficiency. From the simulation results it has been found that the transient performance and steady state performance is improved using PID-controller. The open loop and closed loop controlled QBC are modelled and simulated using MATLAB simulink and found that the closed loop PID-controller gives satisfactory response, good output voltage regulation and maintains constant voltage. The experimental results are found to be more advantages and cost effective with microcontroller. QBC has advantages like reduced hardware, low switching loss and less switching stress. Simulation results are in line predictions.

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A Closed Loop Control of Quadratic Boost Converter Using PID-controller

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چکیده

در این مقاله به کارگیری کنترل باز و بسته تبدیل کننده تقویتی چهارتایی (QBC) با استفاده از کنترلر PID مورد بررسی قرار می گیرد. QBC شامل تبدیل کننده تقویتی و پرواز برگشت توسط یک تک سوئیچ است. به طور ویژه، QBC برای تنظیم رابط DC بین میکروسورسهای مختلف و اینورتر DC-AC با شبکه برق طراحی شده است. QBC و کنترلرهای P، PI و PID به کمک شبیه ساز MATLAB مدل شده و مورد مقایسه و بررسی قرار گرفتند. مشخص شد که عملکرد حالت گذرا و ماندگار با استفاده از کنترلر PID بهبود یافته است. این تبدیل کننده به ولتاژ گام بالای خوبی با نسبت بار مناسب و استرس ولتاژ پایین روی سوئیچ قدرت دست می یابد. حلقه باز شبیه سازی شده و عملکرد حلقه بسته به شکل تجربی تأیید شدند.

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