Performance Analysis of Hybrid Electric Vehicle Battery Charger Using Voltage Oriented Control

Nagm Eldeen Abdo Mustafa Hassanain, Abdelaziz Y. M. Abbas, Mohammed Hassan Ahmed

Abstract — In this paper, a high performance battery charger is designed to charge the batteries of hybrid electric vehicles. The charger of hybrid electric vehicle battery must be fully adapted to the battery to preserve the battery from damage and prevent harmonic current in the grid. Three-phase boost rectifier (universal bridge) using diode and isolated gate bipolar transistor is used. It has advantages of Bi-directional power transfer capability and unity power factor operation. The voltage Oriented Control method is used to control the DC output voltage. Matlab/Simulink software is used to simulate the mathematical model. The DC output voltage with unity power factor is obtained.

Index Terms— *Battery charger, hybrid electrical car, boost rectifier, voltage Oriented control*

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1 INTRODUCTION

A plug in hybrid electric vehicle is a hybrid vehicle which utilizes a battery to power the vehicle's electric motor [1].

A battery charging system is used to draw energy from the grid, store it in a battery, and release it to the power device. The charger must be fully adapted to the battery to prevent battery from damage. The charger system needs to work with any kind of electric [2-5].

The design of an outlet battery charger is not as simple as connect the battery straight to the grid. The power charges the battery must be within certain specifications to prevent damage to the battery and overall system. In terms of plug in Hybrid Electric Vehicle (HEV), the high- energy battery pack is to be charged with Power Factor Correction (PFC) from an AC outlet. The most common topology for the HEV battery charger is the two-stage approach with cascaded, PFC AC-DC and controller of the converter. In the PFC AC-DC stage, AC three phase is rectified and boosted with power factor correction. The output of the boost converter is connected to the DC bus. The second stage controlled the output voltage of the converter.

The charger system needs to work with any kind of electric car. The most important issues are the voltage level differences of batteries between different electric car models. The battery voltage can vary from 60 V to 400 V [6]-[7].

There are many converters topology method used to covert the AC to DC [8-10]. In this paper three-phase boost rectifier using diode and isolated gate bipolar transistor is used. It has advantages of Bi-directional power transfer capability and unity power factor operation. In order to achieve this voltage oriented control (VOC) method is used. The VOC guarantees high dynamic and static performance via an internal current control loop. But the quality depends mainly on the current control strategy [11].

2 CONVERTERS TOPOLOGY AND PRINCIPLE OF OPERATION

In power electronic systems the rectifiers are commonly applied in the front end of DC-link power converters as an interface with the ac line power [12-14].

2.1 Rectifier Topologies

As a consequence for problems of diode rectifier many new switch-mode rectifier topologies that comply with the new standards have been appeared and developed to limit the harmonic content of the current drawn from the power line by rectifier. The aim of the paper is to develop a three phase charger with unity power factor operation.

2.2 Simple solution of the boost converter

The topology shown in Figure 1 presents a simple solution of boost-type converter with the possibility to increase DC output voltage. This is an important feature of converters giving maximum DC output voltage. The main drawback of this solution is stress on the components and low-frequency distortion of the input current [8].

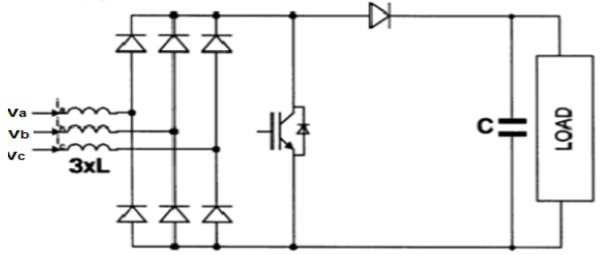

Figure 1 Simple solution of the boost converter

2.3 Rectifier Using PWM Modules

Figure 2 shows topology using PWM rectifier modules with a very low current rating (20-25%) level of rms current. Hence it has a low cost potential and provide only the possibility of regenerative braking mode with active filtering, but the DC regulation is difficult [8].

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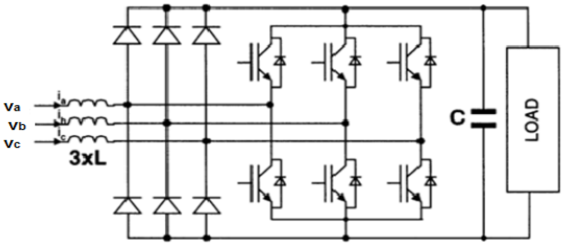

Figure 2 Rectifier Using PWM Modules

2.4 Vienna rectifier

Figure 3 presents a three-level converter called a Vienna rectifier. The main advantage is low switch voltage, but non typical switches are required. It has high power density and unidirectional power flow. It can also provide UPF [8].

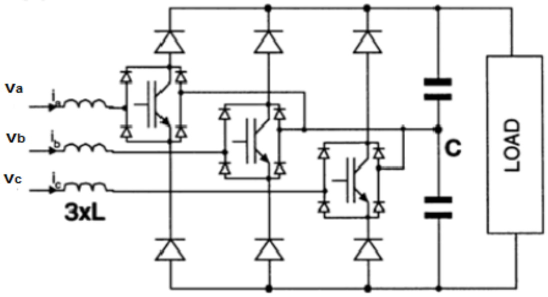

Figure 3 Vienna rectifier

2.5 Universal bridge topology

Figure 4 presents the most popular topology used, and more recently as a PWM rectifier [8]. This universal topology has the advantage of using a low-cost three-phase module with a bidirectional energy flow capability. Although, it has disadvantages of a high per-unit current rating, poor immunity to shoot-through faults, and high switching losses.

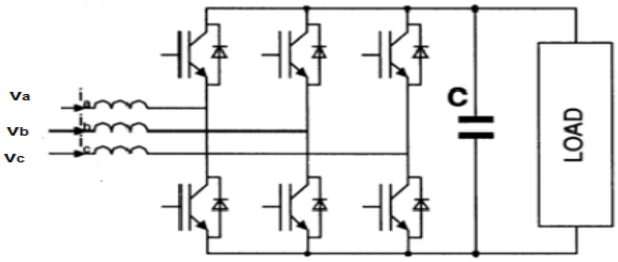

Figure 4 Universal bridge topology

3 CONTROL TECHNIQUE OF PWM RECTIFIER

The control techniques of PWM rectifier can be generally classified as Direct Power Control and Voltage Oriented Control.

3.1 Direct Power Control (DPC)

The Direct Power Control (DPC) is shown in Figure 5. It is based on the instantaneous active and reactive power control loops. In DPC there are no internal current control loops and no PWM block, because the converter switching states are selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power. The reactive power q_{ref} set to zero for unity power factor.

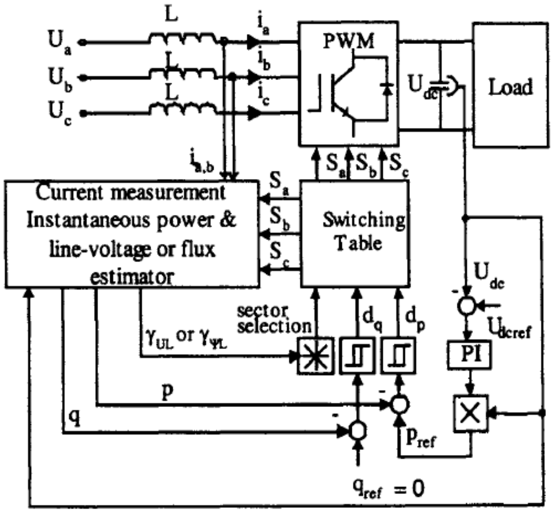

Figure 5 Direct power control scheme

3.2 Voltage Oriented Control (VOC)

The Voltage Oriented Control is based on a series of transformations from a three phase stationary reference system *abc* to a synchronous rotating reference system *d-q* through a two phase stationary reference system *α-β*. With these transformations, the control voltages remain constant and become DC values, making all the control process more simple. A closed-loop current control is used. A scheme of the Voltage Oriented Control is shown in Figure 6.

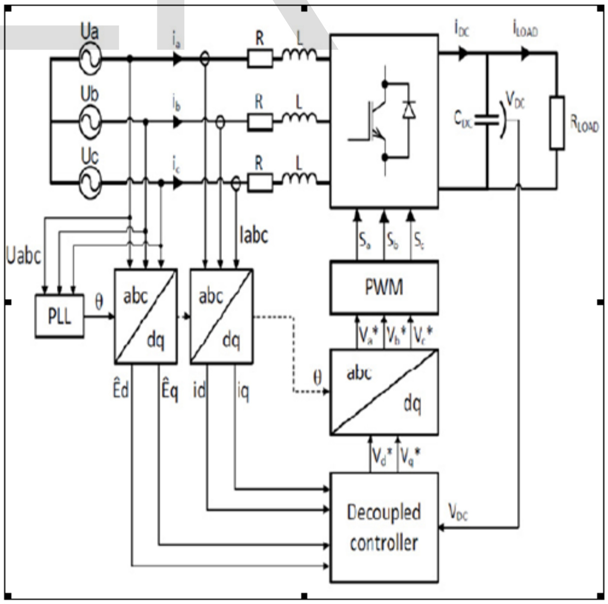

Figure 6 Voltage Oriented Control scheme

These control strategies (DPC and VOC) can achieve the same main goals, such as high power factor and near sinusoidal input current waveforms. The DPC has variable switching frequency and VOC has fixed switching frequency [8],[11].

By comparing both control method the voltage oriented control is chosen in this paper because it has more advantages than the other methods.

According to the specifications of rectifier topologies and control strategies, the universal bridge topology and voltage control strategy has been chosen to simulate the battery charger. Boost rectifiers are built with semiconductors with gate-turn-off capability. The gate-turn-off capability allows full control to the converter, because valves can be switched ON and OFF whenever required. This allows commutation of the valves hundreds of times in one period which is not possible with line-commutated rectifiers, where thyristors are switched ON and OFF only once a cycle. This feature confers the following advantages [10]:

- The current or voltage can be modulated (pulse width modulation),
- generating less harmonic contamination,
- the power factor can be controlled, and it can even be made to lead, and
- Rectifiers can be built as voltage or current source types.

4 MODEL OF THE HEV BATTERY CHARGER

The model of the HEV battery charger used in this paper is used VOC method. The main blocks of the model are: phase look loop, decoupled controller, PI controller, batteries and current controller.

4.1 Phase Look Loop (PLL)

The phase look loop is an electric feedback circuit consists of phase detection, a low pass filter and voltage controlled oscillator (VCO). It is capable of looking auto or synchronizes with an incoming signal. Its aim is to give the voltage angle of the three-phase system v_a,v_b and v_c. This angle is then used for all the *dq* transformations in the model.

4.2 Decoupled Controller

Figure 7 shows the decoupled controller block. The block consist of current controller, Proportional Integral controller (PI) and v_{dc} link, and the output of decoupled controller is $v_d{}^*$ and $v_q{}^*$.

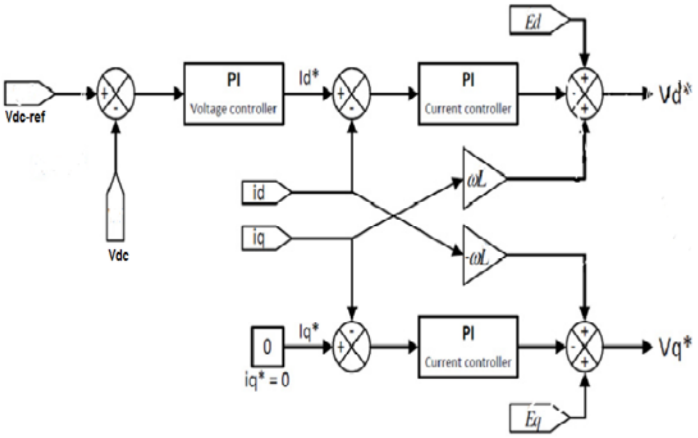

Figure7 Decoupled controller (current and DC-link voltage controller)

4.3 PI Controller

The PI controller reduces the error. The integral action removes the error only if the reference value is constant in steady state. Using Clarke and Park transformations, the current measurements are transformed to DC quantities, then, a simple PI controller can give better results

The main qualities for *dq*-frame current controller are:

- Fast dynamic response.
- Better accuracy current tracking.
- Less sensitive to parameter variations

The PI Controller block generates an output signal based on the difference between a reference signal and a measured system output. The block computes difference signal for each of the proportional [15].

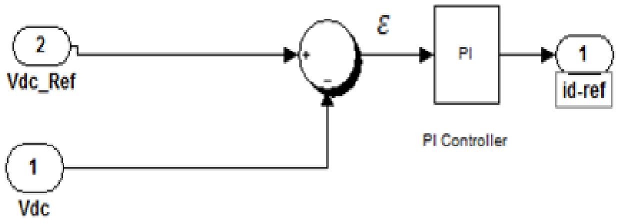

Figure 8 Simulink of DC-link voltage controller

The ultimate goal of the PI controller is to obtain a desired voltage in the DC-link. By measuring the instantaneous voltage and comparing its value with the value of the reference voltage as shown in Figure 8. The error ε that is fed to the controller is obtained as follow.

$$\varepsilon = v_{dcref} - v_{dc} \qquad (1)$$

By implementing a PI control, a reference current for the system, i_d, is calculated as follow

$$i_d^* = k_p\varepsilon + k_i\frac{\varepsilon}{s} \qquad (2)$$

k_p: Proportional gain of the controller
k_i: Integral gain of the controller

4.4 Current Controller

Once a DC-link voltage control is established, the reference current I^*_d , which is used to control the DC voltage, is obtained. In addition, due to the unit power factor operation of the system, the *q*-axis reference current I^*_q is set to zero. To obtain these reference currents in the system, a current control is performed, and the resulting of current controller in a reference voltage is calculated in the *dq*-axis system. The simulation of the controller is done for two PI control loops, one for each component of the current I^*_d and I^*_q . The outputs of the two PI controls are v^*_d and v^*_q respectively as shown in Figure 9 [8]. The components of this reference voltage are obtained using equations below [4].

$$v_d^* = E_d - K_p\varepsilon_d - k_i\frac{\varepsilon_d}{s} + wLI_q \qquad (3)$$

Where

$$\varepsilon_d = I^*{}_d - I_q \qquad (4)$$

$$v_q^* = E_q - K_p\varepsilon_q - k_i\frac{\varepsilon_q}{s} + wLI_d \qquad (5)$$

5 HEV BATTERIES

There are many types of batteries used in HEV, Lead acid, nickel-cadmium and lithium-ion. One of the primary goals of this research is to charge a high power battery. The battery selected is the Lithium Ion Battery type [15].

Figure 9 shows the complete block diagram of voltage oriented control scheme, firstly the line voltage v_{abc} need to feed the PLL, and the voltage angle is obtained to use for three-phase stationary to *dq* coordinate transformation of line current and voltage. Secondly, the *dq* coordinate values and the DC-link voltage value are used in a controller, the controller compare these values using PI controller. Finally, the reference voltages created by the controller are sent to the PWM block to create the switching patterns S_{abc}, (S = 1 means switch ON, S=0 means switch OFF), to pulse the converter.

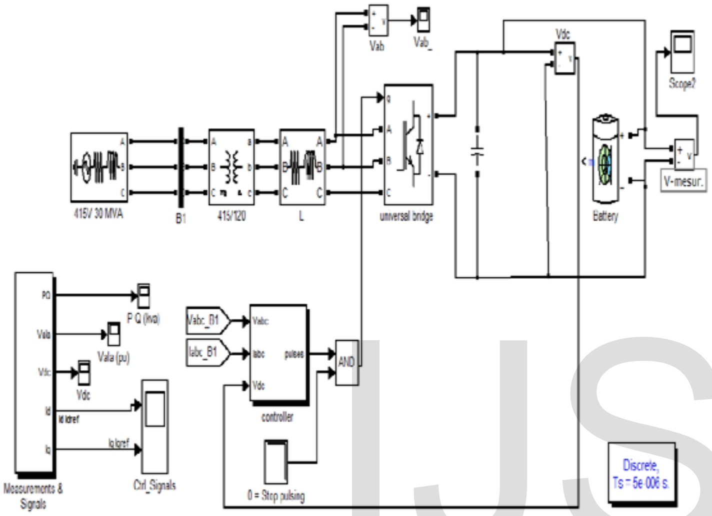

Figure.9 Complete model of the battery charger using (VOC)

6 SIMULATION RESULTS

Based on the mathematical models, the voltage oriented control of boost PWM converter is used to simulate the battery charger and built in MATLAB/SIMULINK software. The results are obtained for two DC reference voltages equal to 200V and 300V. First, the results are obtained with stopped pulsing which means that the converter worked as the diode rectifier. In the second case the pulse is activated and the boost PWM converter voltage oriented control is worked. The results of the two cases are compared and discussed.

6.1 Simulation with stops pulsing:

Figure 10 shows The DC output voltage of the complete model with stopped pulsing (pulses normally sent to the converter are blocked). From Figure 10 there is initial overshoot for the first 0.01s. This due to switching frequency reached. Then the DC-output voltage decays gradually. At t=0.01s the pulses are blocked and the DC voltage drops to 250 V. Also, it can be observed that when the pulses are blocked, the models operation becomes similar to a three-phase diode bridge rectifier. Consequently ripple in the DC voltage output is observed.

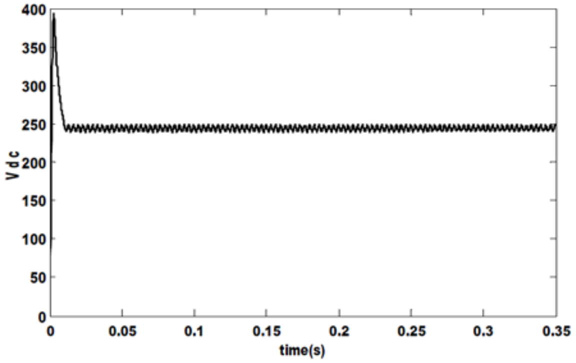

Figure10 DC output voltage when stop pulsing (uncontrolled rectifier)

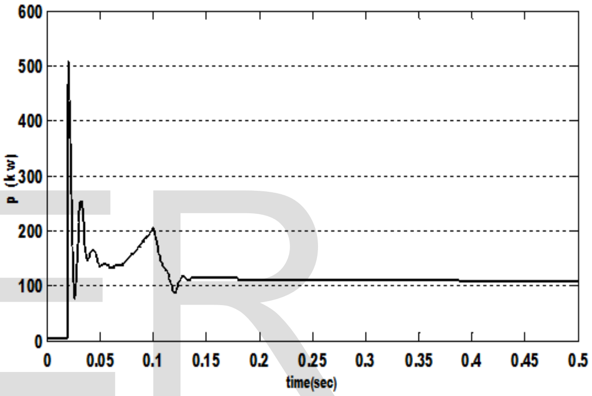

Figure 11 Active power in (kw)(uncontrolled rectifier).

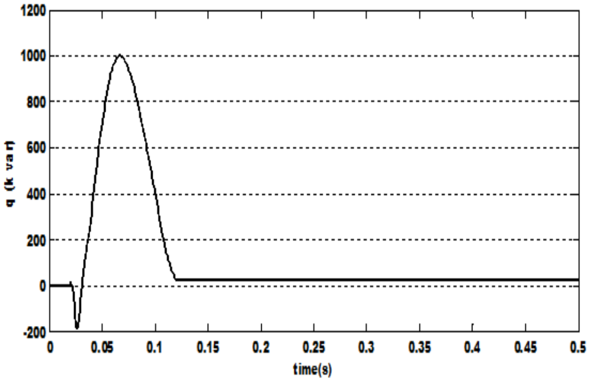

Figure 12 Reactive power (k var), (uncontrolled rectifier)

Figures 11.and 12 show the results of active and reactive power during stopped pulsing. Figure 11 shows that the active power has initial overshoot and then settled at 0.1s with a value of 115 KW. Figure 12 show that the reactive power is 25KVAR. This means that the system is not in unity power factor, which indicates that this model generate harmonic.

6.2 Simulation of the battery charger when $V_{dc\text{-}ref}$ =200V

When the system is under control and pulses are activated the DC output voltage is smooth. Figure 13 presents the DC output voltage of the boost converter using voltage oriented control when $V_{dc\text{-}ref}$ is set to 200V. The DC output voltage has initial overshoot reach to 340V at the first 0.1s, and then the DC output voltage is 200V. Therefore the charger is fully adapted due to use of PWM scheme rectifier and VOC.

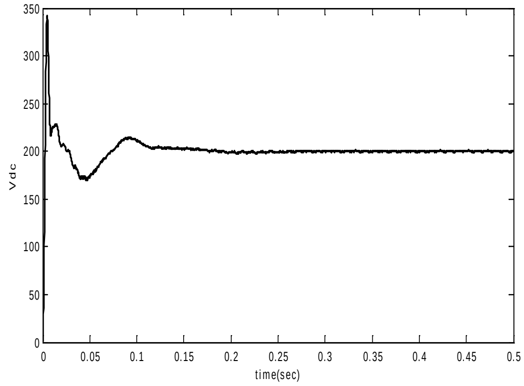

Figure13. DC output voltage of the model when Vdc-ref =200V

Figure 14 illustrates the active power of the PWM converter using voltage oriented control, at t =0.1s the active power is 15KW. Figure 15 shows the reactive power. It can be observed from Figure 15 that the reactive power is equal to zero. This is due to the use of PWM converter topology and VOC scheme which is achieve the unity power factor for this system.

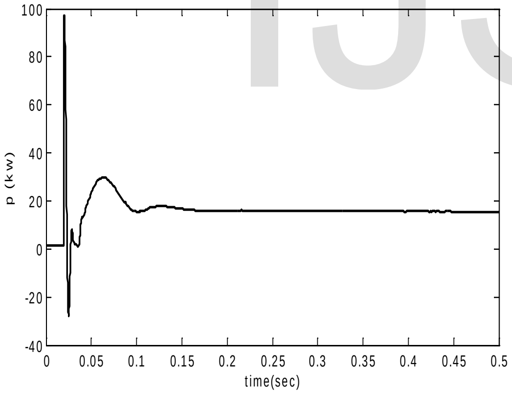

Figure 14 Active power of the system model when Vdc-ef =200V

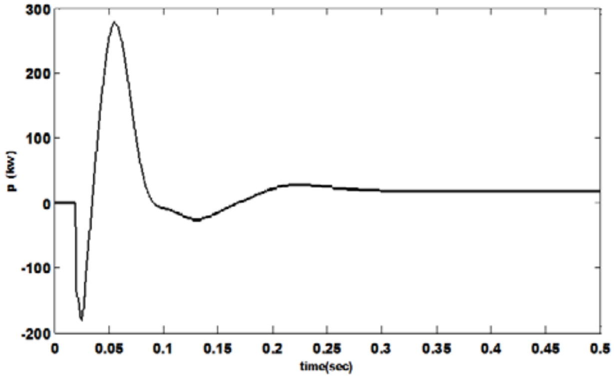

Figure15 Reactive power of the system model when Vdc-ref =200V

6.3 Simulation of the battery charger when $V_{dc\text{-}ref}$ =300V

Figure 16 shows the DC output voltage of the model, it has initial overshoot reach to 340V at the first 0.1s, then the DC output voltage is 300V, this means that the charger is fully adapted.

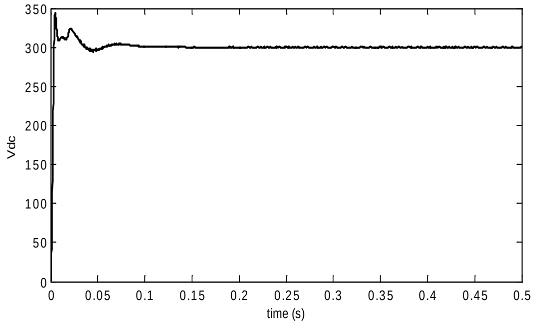

Figure 16 DC output voltage of the model when Vdc-ref =300V

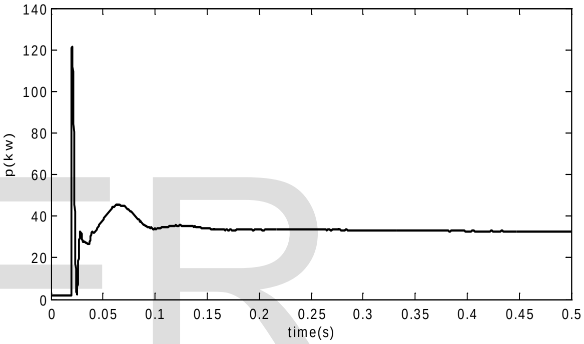

Figure17 Active power of the system model when Vdc-ef =300V

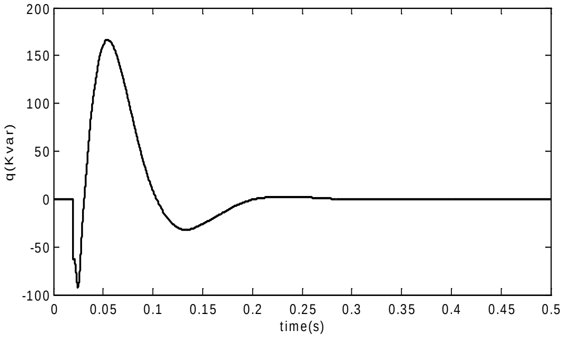

Figure 18 Reactive power of the system model when Vdc-ref =300V

Figure 17 presents the results of active power of the PWM converter using voltage oriented control with $V_{dc\text{-}ref}$=300V and the active power has a value of 35KW. Figure18 shows the reactive power and it can be observed that the reactive power is zero, which means the system has unity power factor.

7 COMPARISON BETWEEN THE THREE CASES RESULTS

Table 1 shows the results of the complete simulation model when the pulses are blocked (diode rectifier), and the results of the simulation system using Voltage Oriented Control with $V_{dc\text{-}ref}$=200V and 300V. From the Table 1 it can be observed that the DC output voltage using diode rectifier is 250V because the system is uncontrolled, and the active power the reactive power are 115KW and 25KVAR respectively, which means that there is ripple in the system. Also, Table 1 shows that the output active power when using voltage oriented control is increased with $V_{dc\text{-}ref}$ is 300V than $V_{dc\text{-}ref}$ is 200V. However, the reactive power is remained zero which means that the system is worked at unity power factor.

TABLE 1

THE RESULTS OF THE COMPLETE SIMULATION

Output	DC voltage (V)	Active power (kW)	Reactive power (kvar)
Diode rectifier (stop pulsing)	250	115	25
Voltage oriented control with $V_{dc\text{-}ref}$ = 200V	200	15	0
Voltage oriented control with $V_{dc\text{-}ref}$ =300V	300	35	0

8 CONCLUSIONS

In this paper the system model and simulation of the three phase boost PWM converter using voltage oriented control technique is presented. This model is used as the battery charger to charge hybrid electric vehicle battery. The mathematical model is developed and Matlab/Simulink software is used to simulate the model. The simulation results have shown an accurate response to DC voltage requirements. Regarding power quality, the system satisfies the requirements and accomplishes a power factor correction. The unity power factor is achieved by using PWM rectifier topology and voltage oriented control VOC scheme.

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