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THREE-PHASE BUCK TYPE PFC RECTIFIER FOR ELECTRICAL VEHICLE BATTERY CHARGER

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Abstract- Three-phase AC/DC buck-type power factor correction (PFC) rectifier is presented in this paper. State of the art three-phase AC/DC rectifiers and improvements of the rectifier topologies are researched in this study. The SWISS Rectifier is implemented for Electrical Vehicle (EV) battery charger with 220 $V_{LN\text{-}rms}$ / 50 Hz three-phase input. The SWISS Rectifier for EV charger application is implemented by means of simulations. Depending upon the battery pack needs, 48 VDC output voltage is examined under both steady-state and dynamic load change conditions.

Keywords: Power Factor Correction, PFC, Electrical Vehicle, Battery Charger, Buck Type PFC, Harmonic, SWISS Rectifier.

I. INTRODUCTION

As the technology develops, the interest in EV technologies are growing. It is desired to have long life-time batteries and short battery charging time. The long life batteries can be managed by both battery technology and battery charger technology. Determining a battery charging algorithm and charging method in accordance with battery technology ensures that the battery life is effective. Fast and efficient battery chargers are needed to reduce battery charging time. AC voltage is converted to DC voltage in grid-connected battery chargers. The high efficient battery chargers ensure unity power factor on the grid side and low input current harmonics. In addition, DC output voltage of a high quality battery charger must be controllable, well-regulated and have high dynamic response performance for fulfilling battery pack voltage requirements.

Generally, the EV battery chargers are implemented by using two-stage power converter structures. AC grid voltages are converted to a high DC bus voltage by utilizing Power Factor Correction (PFC) rectifier, and then a DC/DC converter takes place in to regulate the battery voltage. The EV battery charger can be either on-board or off-board [1]. The system efficiency from end to end (from AC input voltage to Battery DC output voltage) is the product of the efficiency of two separate power converters. Thus, the total efficiency is not too high with a two-stage converter and also, the DC bus capacitors are needed to regulate the high voltage DC power bus in this power system architecture.

Boost-type PFC rectifiers provide a high DC output voltage. This high DC output voltage cannot be directly used to charge the battery pack. A dc-dc converter must be utilized to reduce the high DC voltage to low DC voltage suitable for battery. For direct connection of the PFC output to the battery, buck-type PFC rectifiers can be preferred for EV chargers. If a galvanic isolation of battery from grid is required for the sake of safety, an isolated DC-DC converter can be added in series [2]. The output voltage of the buck-type PFC can be controlled with a wide range and this is another advantage over boost-type PFC. Especially in three-phase PFC rectifiers, the output voltage has a very wide control range. This advantage can be utilized in dc power distribution systems.

In this paper, it is proposed to convert the three-phase 220 $V_{LN\text{-}rms}$ / 50 Hz AC input voltage directly to 48 VDC by means of a single converter for battery charger of electrical vehicles. Single stage AC/DC power converters are investigated and recently the improved SWISS rectifier is applied. The study is supported by the simulation results. In Section II, AC/DC rectifiers are presented and passive diode rectifier, active controlled boost-type and buck-type PFC rectifier topologies are given. In Section III, SWISS rectifier, buck-type PFC, is examined. SWISS rectifier with 220 $V_{LN\text{-}rms}$ / 50 Hz input and 48 VDC is simulated. In Section IV, the simulation results are demonstrated.

II. AC/DC RECTIFIERS

Unregulated DC voltage can be obtained by rectifying AC input voltages with diode rectifier and then filtering with capacitor, in the first generation applications. The unregulated DC voltage obtained at the output of the diode rectifier shown in Figure 1 can be regulated by means of the DC/DC converter. In this type of converter, when AC input voltages are converted to DC voltage by using diode rectifier without supervision, both total harmonic distortion values of input currents are high and input power factor is low. This generally results in a lower efficiency of the rectifier. It causes the currents with high peak current values to be drawn from the input and thus leads to thick and heavy input cables. It also causes diodes with high rated current values. This leads to the need for diodes with high rated current values.

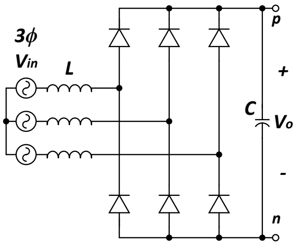

Figure 1. Three phase uncontrolled rectifier

The AC to DC rectification causes harmonics on AC input currents and phase margin between AC voltage and AC current. The harmonics and the phase shift, negatively affect the efficiency of the converter. In order to increase the efficiency, the harmonics on AC input current should be eliminated and the phase shift should be minimized. By using the controlled AC/DC conversion, input current harmonics can be eliminated, sinusoidal waveforms can be obtained and the input power factor can be approximated to unity.

In the literature, various power electronics circuit topologies for converting three-phase AC input voltages to DC voltage are included. PFC circuit topologies are used in order to have sinusoidal input current waveforms with reduced harmonic distortion and to obtain regulated DC output voltage [1], [2], [3] and [4].

The PFC technology produces sinusoidal input currents and unity power factor in the AC side. The PFC output voltage is controllable and can be either increased or decreased. Depending upon the ratio between the output voltage to the input voltage, PFC circuits can be divided into two groups as boost-type PFC and buck-type PFC. In boost-type PFC, the inductor is at AC input side. The output side has high voltage stress in the boost-type PFC topologies [19], [20]. The output capacitor has to be selected with high rated voltage. The output ripple can be higher in boost-type PFC compared to buck-type PFC. In the buck-type PFC, the inductor is at the DC output side and hence by having second order LC-type low-pass filter at the output side, the output ripple in the buck-type PFC is low. Due to the low output voltage in buck-type PFC, the low rated voltage capacitors can be used at the output.

The technological developments of EV battery chargers play an important role in the development of EV technology. The properties of the battery charger directly affect the battery life-time and the charging time of the battery. A high efficient and high reliable battery charger is highly demanded. High efficiency causes high power density, low weight and low volume, technologically.

An EV charger must guarantee that the *THD* of AC input current is low and the power factor is high. By this way the grid power quality is protected. At rated power, it is desired to have a *THD* of AC input current lower than 5% for industrial applications. The standards limit the maximum allowable harmonics on the AC input current. The qualified EV chargers must comply with the harmonic limits specified in the standards [1].

An efficient and low size battery charger yields advantageous results in terms of electrical power budget, weight budget and thermal emission. With the development of PFC circuits, the problems of regulation of input current harmonics, input power coefficient and output voltage of conventional converters have been largely eliminated [6], [7], [8] and [17].

The ratio of the DC output voltage to AC line-to-line peak voltage ($K_{CR} = V_{out}/V_{LL\text{-}peak}$) can be defined as voltage conversion ratio (K_{CR}) of the rectifier. The K_{CR} is greater than 1 for boost type PFC rectifiers where the K_{CR} is smaller than 1 for buck type PFC rectifiers.

Figure 2 shows a single-switch PFC circuit topology and Figure 3 shows a six-switch PFC circuit topology. Both circuit topologies are boost type PFC rectifier.

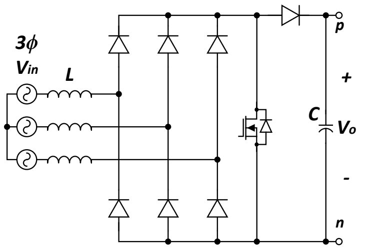

Figure 2. Three-phase single switch PFC rectifier

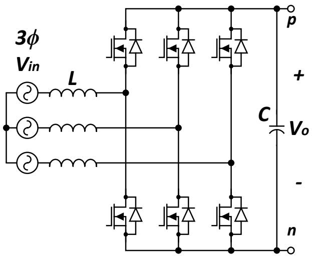

Figure 3. Three-phase six switch PFC rectifier

The circuit topology shown in Figure 4 shows a buck type PFC circuit topology. The inductors in AC side are shifted to DC side in buck type PFC rectifier.

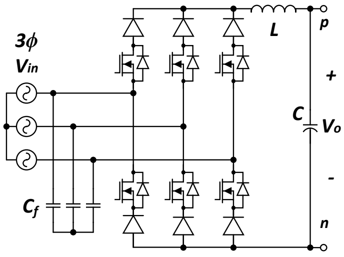

Figure 4. Three-phase six switch Buck-type PFC rectifier

Researches are going on to increase the efficiency and to improve the performance of PFC. There exist many PFC configurations in the literature. One of the main configuration is Vienna Rectifier. Circuit diagram of the Vienna rectifier topology given in Figure 5 is derived from the three-phase PFC topology, as described in articles [9], [10] and [11] published in 1994, 1996 and 1997. The Vienna rectifier topology has similar features to the three-phase PFC topology, but it is more advantageous in terms of efficiency.

In this rectifier, AC type switches are located between the midpoints of the diode rectifier (a, b, c) and the midpoint (M) of the DC bus capacitors. The common mode noise is reduced as a result of the combination of all three phases with the star connection at the midpoint of the DC bus capacitors.

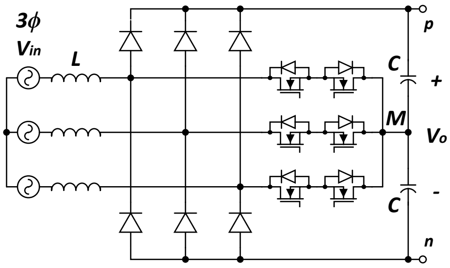

Figure 5. Three-phase Vienna Rectifier

In the Vienna rectifier, the voltages of the capacitors in the DC bus must be balanced and this may lead to an increase in the complexity of topology control. In addition, the large size of these capacitors leads to an increase in the volume of the rectifier. In the study conducted in [12] and [13], the DC bus capacitors were removed and replaced by two semiconductor switches. The topology developed in the study of [13] is called KOREA rectifier and the circuit diagram is shown in Figure 6. Another difference from Vienna rectifier is that the inductors in the input side are shifted to between the common points of the newly added switches and the star point of the AC switches. Removing the output bus capacitors, the KOREA rectifier brings some advantages such as size and ease of control algorithm.

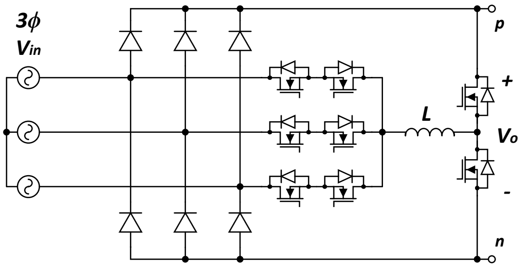

Figure 6. Three-phase KOREA Rectifier

Since the KOREA rectifier does not have any DC output capacitor to hold the output DC voltage, the output voltage ripple increases and thus the output voltage regulation is negatively affected. The output voltage controller cannot be constructed properly. On the other hand, it is possible to control the output power where the output power can be kept constant for various load conditions.

In this study, recently improved SWISS rectifier which is a buck-type PFC is implemented.

III. SWISS RECTIFIER

In the recently improved buck-type PFC rectifier, DC/DC buck converters are integrated to three-phase PFC rectifier [5], [14] and [15]. This topology is called as SWISS rectifier and given in Figure 7. In this topology, capacitors are not located at the high DC bus link and have a regulated output voltage. The three-phase AC input voltages can be directly converted to low DC voltage levels by means of the SWISS rectifier [18]. In order to reduce the common mode noise, the total DC inductance is divided into two for the positive output DC bus and negative output DC bus as seen in Figure 7.

Unlike the six switch Buck-type PFC rectifier (Figure 4); the modulation algorithms in the SWISS converter are simple. Furthermore, because of the inductors on the output, "free-wheeling" diodes are needed to maintain the continuity of the output current, which is inherent in the output of the SWISS topology. However, in order to ensure the continuity of the inductor current in the six switch Buck-type PFC rectifier, a free-wheeling diode must be added to the circuit.

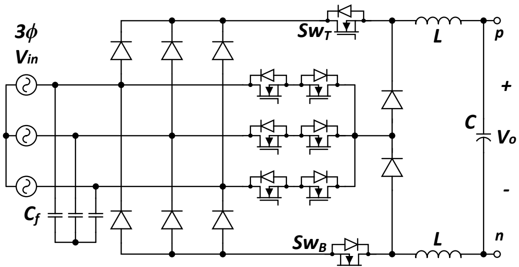

Figure 7. Three-phase SWISS Rectifier

The control of SWISS rectifier is shown in Figure 8. For the regulation of the output voltage, the output DC voltage is measured (V_{o_meas}) and compared with the reference output voltage (V_{o_ref}) in the outer loop. In inner loop, the inductor current is measured (I_{L_meas}) and compared with the reference inductor current (I_{L_ref}) which is derived by the controller in the outer loop. The controller loops generate reference controller signal. The Scaling term is to normalize the controller signal for the modulator block. The modulator generates the switching signals of Sw_T and Sw_B by using the reference controller signal.

Depending upon the phase of three phase AC input voltages, the phase selector block generates the switching signals of the AC switches of the SWISS Rectifier as given in Figure 8.

In this study, the SWISS rectifier is implemented to electrical vehicle battery charger application with very small voltage conversion ratio. In the previous studies, K_{CR} was approximately 75%. The K_{CR} is implemented as <70% for the first time in this study. While the K_{CR} is getting smaller, the control algorithm has a challenge to regulate the output voltage and to have high dynamic performance.

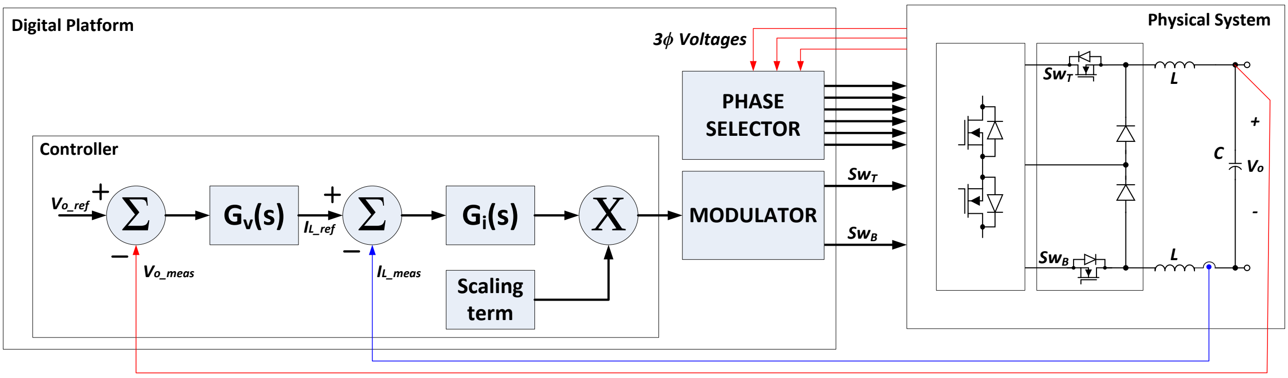

Figure 8. Controller structure of the SWISS Rectifier

IV. SIMULATION RESULTS

In this section, the performance of the SWISS rectifier is studied by utilizing computer simulations. The SWISS rectifier is fully modeled.

A SWISS rectifier with three-phase 220 $V_{LN\text{-}rms}$ / 50 Hz input and 48 VDC, 1.2 kW output is simulated. The parameters of AC filter, the parameters of DC filter, AC input voltage/frequency, switching frequency and the DC output voltage are given in Table 1.

In Figure 9, the waveforms of AC line-to-line voltages and busbar voltage (voltage between the common point of bottom diodes anodes and the common point of top diodes cathodes) are shown. As can be seen from the figure, the busbar voltage follows the envelope formed by the line-to-line AC input voltages maximum value and it is seen that there are transitions with 60° sections.

Table 1. SWISS Rectifier Parameters

Parameter	Value
AC Input Voltage ($V_{ln\text{-}rms}$)	220 V_{AC}
AC Input Frequency	50 Hz
AC Filter Inductor	10 µH
AC Filter Capacitor	6.8 µF
Switching Frequency	150 kHz
Output Power	1200 W
DC Output Voltage	48 V_{DC}
DC Output Inductor	20 µH
DC Output Capacitor	470 µF

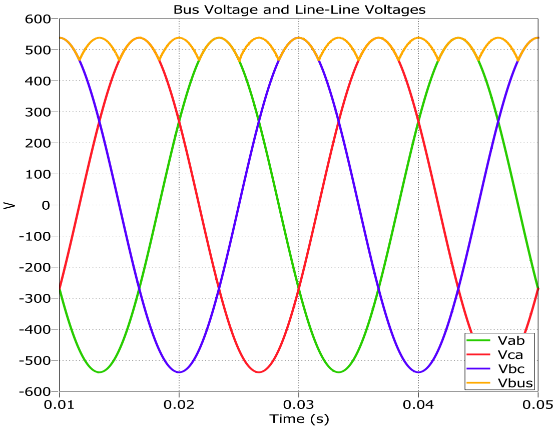

Figure 9. Rectified DC bus voltage (V_{bus}) and AC line-to-line voltages under steady-state conditions

The AC input currents and AC line-to-neutral voltages under steady-state full load conditions are in Figure 10. The AC input current is in the sinusoidal waveform and they have low *THD*s. When the corresponding voltage is maximum or minimum, the current ripple is low relatively. When the voltage waveform is in medium region between three phases, ripple of the corresponding current has higher ripple. There exist some distortions on AC input currents on the section transitions.

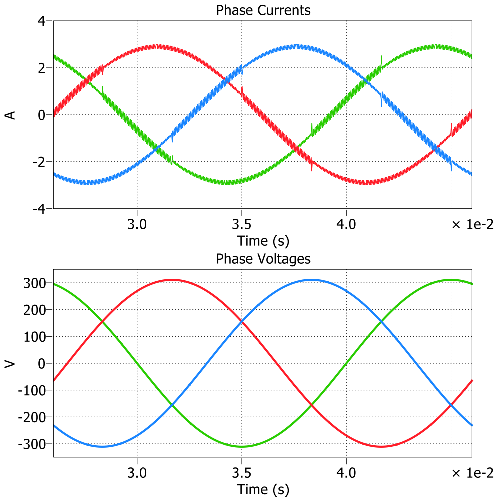

Figure 10. AC Input currents and AC input voltages under steady-state conditions

Under steady-state full load conditions, the load current and the output voltage are as in Figure 11. The regulation of the output voltage is stable as expected.

In order to test the dynamic behavior of the SWISS rectifier, step load change is applied. The step load test is performed by increasing the load from half to full at 2.5ms instantly. The AC input currents and AC line-to-neutral voltages under step-load change are given in Figure 12. AC input currents have some distortion at the instant of load change. Approximately 20% overshoot is observed on the green phase which is maximum at 2.5 ms. For a 50% load change, this overshoot is acceptable. No distortion has been seen on AC line voltages. The waveforms of output voltage and the load current under step-load change are given in Figure 13.

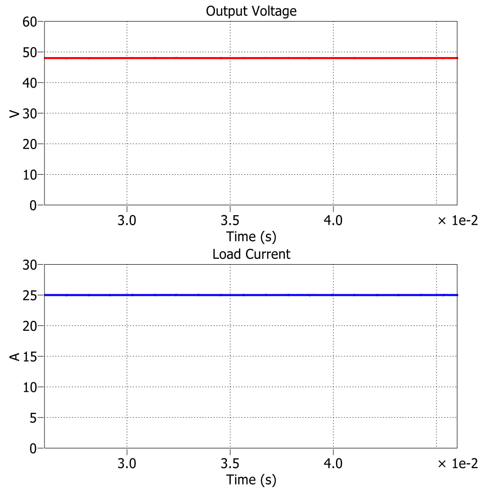

Figure 11. DC output voltage and load current under steady-state conditions

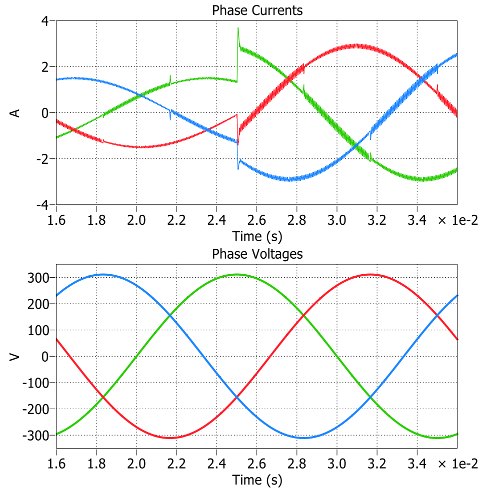

Figure 12. AC input currents and AC input voltages under step load change from half load to full load condition

The closer view of dynamic characteristics for output voltage and load current is given in Figure 14. It is seen that there is voltage drop (0.5 V) on the output voltage at the instant of step load change and then the output voltage is recovered in less than 150 µsec (~23 PWM cycle) with the fast response of the controller. The controller cannot respond in first 5 PWM cycles and the output voltage drops. The measurement delay, calculation delay and controller adaptation time to new load condition cause the response delay. After first 5 PWM cycle, the controller recovers the output voltage in 18 PWM cycle.

V. CONCLUSIONS

The SWISS Rectifier has been applied for electrical vehicle with three phase 220 V / 50 Hz AC input voltages. In this study, the three-phase AC input voltages are converted to 48 VDC output voltage with a single stage. It has been confirmed by simulation studies that input current harmonics are reduced and the input power factor is approached to 1 when performing voltage conversion ratio (K_{CR}) is less than 10%. By reducing input current harmonics, having a unity power factor and using single stage power converter; the efficiency is increased.

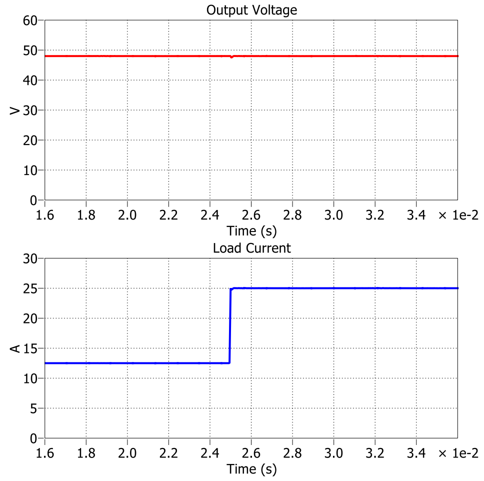

Figure 13. DC output voltage and load current under step load change from half load to full load condition

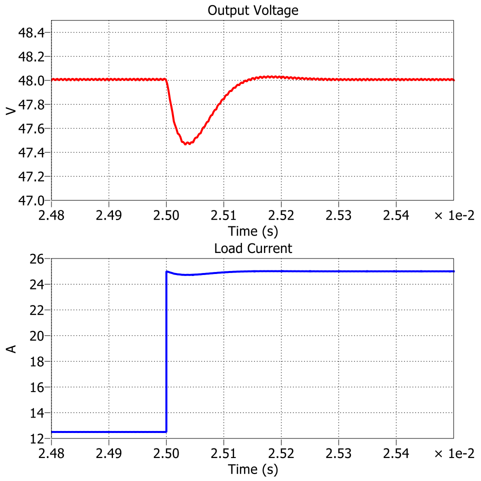

Figure 14. DC output voltage and load current under step load change from half load to full load condition

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BIOGRAPHIES

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