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A Novel Rectification Method for a High Level ac Voltage Converting to a Low Level dc Voltage: Example of Scooters Idling Stop System

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Abstract

This paper proposed a novel rectification method for a high-level ac voltage convert to a low-level dc voltage, in which the Permanent Magnet Synchronous Motor (PMSM) Matlab/Simulink model in generation mode has been established in order to analyze the energy characteristics of PMSM operating in scooters at full drive speed. From the simulation results, the terminal voltage and line current in load-side have a wide convert rate when the internal resistance of battery is a great value. In design, the gate driver signals can be generated, referring to the virtual hall signals, to chop the different back Electromotive Force (back-EMF). Then, the ac voltages of back-EMF can be rectified to the dc voltage by Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) at the same time. Finally, the proposed method has been implemented in scooters idling stop system successfully, and a safe low level dc voltage always can be obtained to charge battery immediately (in general 12V) no matter what a variable speed in scooters.

Keywords: Rectification, Scooter, Virtual Hall Signal, Idling Stop System

1 Introduction

The idling stop system has been used to improve the road emission on vehicle in the past few years. The development of Permanent Magnet Synchronous Generator (PMSG) provides a new selection of motor for industrial application and vehicle engineering. According to the characteristics of PMSG, with the higher speed a three-phase ac voltage conversion will cause the increase of a dc link voltage. However, the dc link output voltage must be fallen within a safe level voltage to charge the battery to guarantee battery safety in terms of the vehicle applications. Typically, a dc/dc converter apparatus or a buck

circuit unit will be added to deal with the higher voltage in the idling stop system that not only it needs extra costs and more space, but also it has a complexity of vehicle control and some losses of conversion. In literatures, it was necessary to add a buck-boost converter behind the three-phase rectifier to control the Insulated Gate Bipolar Transistor (IGBT) switch in order to maintain a fixed dc voltage [1]. The magnetic field of rotor will be changed when the excitation current of the rotor coil was adjusted directly. Thus the three-phase voltage amplitude of stator can be maintained at a fixed value in the variable speed [2]. The dc link output voltage is behaved as an input voltage when the dc link output voltage is higher than the output voltage of the synchronous

generator. At the same time, the Field Oriented Control (FOC) method was used to control the six power transistor to adjust current into the capacitor to regulate dc link output voltage [3]. This paper proposed a rectification method without any dc/dc converter apparatus or buck circuit unit for a high level ac voltage convert into a low level dc voltage. This method can achieve direct modulation of the dc link output voltage to ensure a safe level voltage to charge battery.

2 Configurations of Idling Stop System Scooters

The idling stop system is designed vigorously to improve pollution emission and enhance fuel consumption in the scooters as shown in Figure 1. For this reason, the Integrated Starter Generator (ISG) must have a high torque characteristic to ensure the engine can be cranked when required.

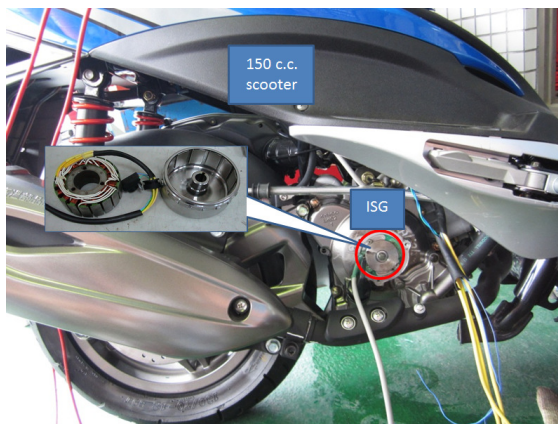


Figure 1: The scooter with idling stop system

Due to the magnets of the rare earth material with a high torque density characteristic, it has a highly suitable capability to apply into the ISG for idling stop system in the scooters. However, the ISG will produce a back Electromotive Force (back-EMF) voltage which will be a higher and higher value when the speed increases, hence the dc link output voltage has similar performance at the dc link terminal as shown in Figure 2.

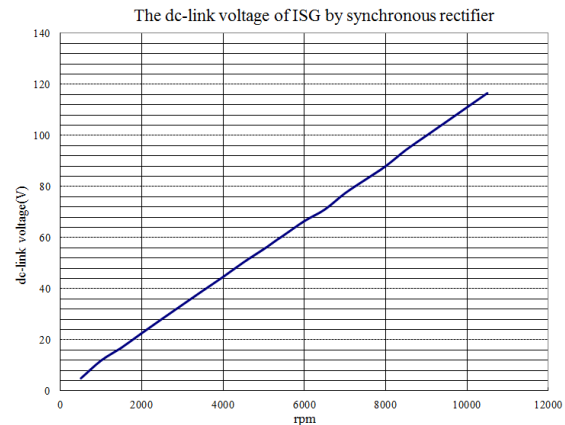


Figure 2: The dc-link voltage of ISG by synchronous rectifier

This paper, the gate driver signals in the generation mode follows a set of three-phase virtual hall sensor signal that is synchronized to the original hall sensor signals, and the six Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) are only turned on or turned off in the 180 ° switching period without any duty given at that time as shown in Figure 3. The strategy refers to the RPM of generator, and then the three-phase virtual hall sensor signals are advanced or delayed some angles to chop a fixed voltage of back-EMF with regard to rectify a safe level voltage at the dc link terminal instantly.

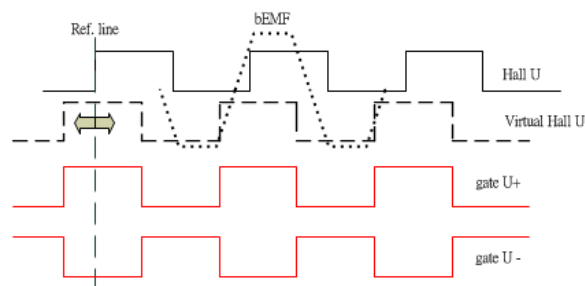


Figure 3: The gate driver signal working

3 Simulation of Generation Mode

3.1 System model

The system model in this research aims for the generation mode of the ISG, and hence the ISG can be modelled as a three-phase balanced ac voltage sources in electric circuit, and connection with a set of MOSFET rectifier. The controller schematic model is shown in Figure 4.

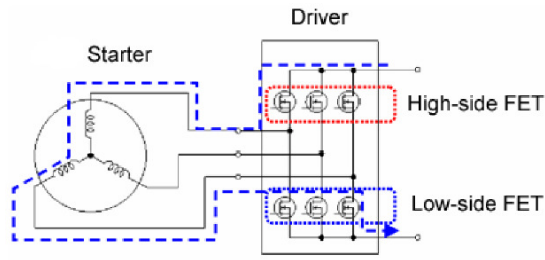


Figure 4: The schematic model of the idling stop system controller [4]

The three-phase input voltages can be described as

$$\begin{aligned} V_{an} &= V_m \sin(\omega t) \\ V_{bn} &= V_m \sin(\omega t - \frac{2\pi}{3}) \\ V_{cn} &= V_m \sin(\omega t + \frac{2\pi}{3}) \end{aligned} \quad (1)$$

Where V_m and ω are the amplitude of the phase voltage and angular frequency respectively.

3.2 Open-circuit analysis

In the open-circuit analysis of the rectifier as shown in Figure 5, some assumptions should be described in simulation section,

Assumption 1: The ac-side wire resistors are considered, but the ac-side inductors are neglected.

Assumption 2: The dc-side resistive load is comparatively larger than the ac-side resistor.

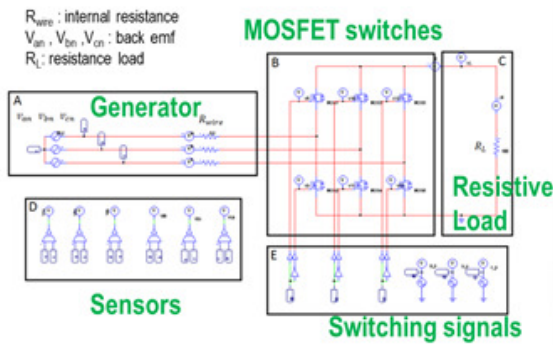


Figure 5: The open-circuit system model

3.3 Analysis of ac-side inductors

In the case of phase angle equals to 60° , the load voltage reaches zero in some points. While further increasing the phase angle, a short-circuit situation happened due to the body diode of MOSFETs being turned on spontaneously. Since the phase angle of 60° is identified as the critical

point of short-circuit, the average and root mean square (RMS) values of the load voltage can be calculated.

In the system model with ac-side inductors, a system analysis based on the rectifier with ac-side inductor and a resistive load is presented in the Figure 6. In order to verify the correctness of the derived load voltages, an example is given to verify the analytical solution. The load voltage can be calculated by superposition and Thevenin equivalent circuit technique. For the switching state as 101 and the phase angle as 0 degree, substituting resistive load $R_L=30\Omega$, wire resistance $R=0.5\Omega$, ac-side inductance $=300\mu\text{H}$, angular frequency $\omega=2000\pi$ rad/s into (2) yields (3).

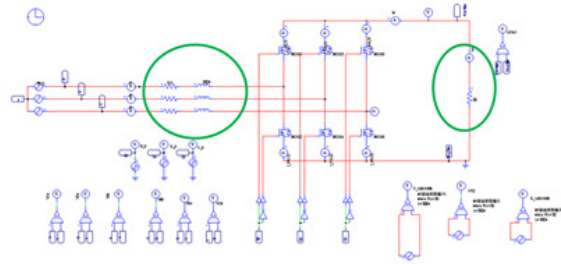


Figure 6: The open-circuit system model

$$V_L = \frac{30}{\frac{3}{2}(R + j\omega L + R_L)} \left(-\frac{3}{2}V_{bn}\right) \quad (2)$$

$$V_L = 38.2 \cos(\omega t - 35.2535^\circ) \quad (3)$$

The derived load voltages in steady state are shown in Table 1.

Table 1: Derived load voltage of six switching states

Switching state	Load voltage
101	$\frac{R_L}{\frac{3}{2}(R + j\omega L + R_L)} \left(-\frac{3}{2}v_{bn}\right)$
100	$\frac{R_L}{\frac{3}{2}(R + j\omega L + R_L)} \left(\frac{3}{2}v_{an}\right)$
110	$\frac{R_L}{\frac{3}{2}(R + j\omega L + R_L)} \left(-\frac{3}{2}v_{cn}\right)$
010	$\frac{R_L}{\frac{3}{2}(R + j\omega L + R_L)} \left(\frac{3}{2}v_{bn}\right)$
011	$\frac{R_L}{\frac{3}{2}(R + j\omega L + R_L)} \left(-\frac{3}{2}v_{an}\right)$
001	$\frac{R_L}{\frac{3}{2}(R + j\omega L + R_L)} \left(\frac{3}{2}v_{cn}\right)$

When the gate driver signals are advanced by the original hall sensor signals, the load output voltages are shown in Figure 7. And, when the MOSFETs are turned off, the decreasing current still goes through the parasitic body-drain diode of the MOSFETs. Hence there is a short-circuited period between every switching cycle.

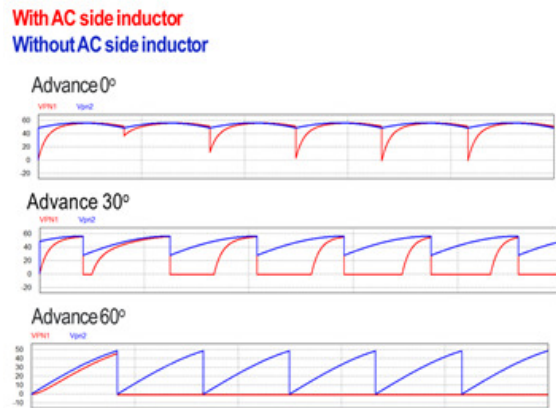


Figure 7: The resistive load voltage under different angles of the gate driver signal

Furthermore in Figure 8, there are similar results of the load voltage in the dc link terminal when the same parameters and advance angles are given in the SimPowerSystems™ and mathematical both.

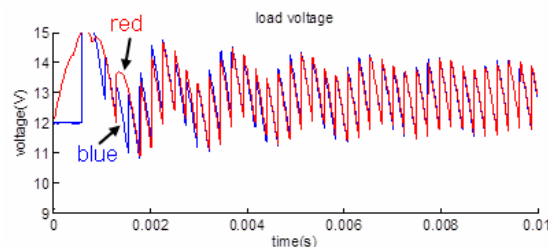


Figure 8: The simulation results of dc link (or load) voltage by mathematical (blue line) and SimPowerSystems™ (red line) method

3.4 Influence of ac-side inductance

A 12V battery load within the open-loop simulation on purpose to analyze the influence of the ac-side inductance on the load voltage, and the battery resistance is 0.03Ω in the SimPowerSystems™. From the simulation results as Figure 9, this rectification method has a larger operation range of the battery charging current with respect to the charging voltage. Besides, connecting extra inductors to the ac-side could be a feasible method to reduce the line current. Also, smaller ac side inductors results in larger operation range of battery charging voltage. However, they cause higher line currents.

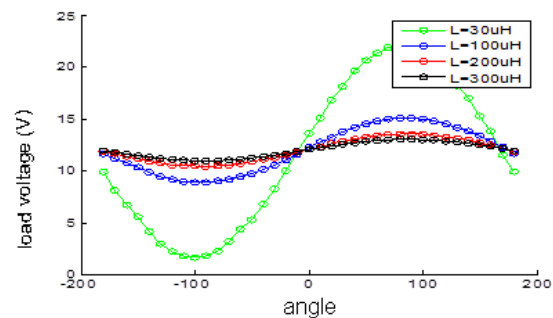


Figure 9: Load voltage with different ac-side inductance

3.5 Closed-loop simulation

A closed-loop simulation of load voltage control and a charging current control were done respectively with a PI controller to confirm the closed-loop system validly. The load voltage control as brief mentioned in Figure 8, and the battery charging current control is shown in Figure 10. The results show the feasibility to control the system by this novel rectification method.

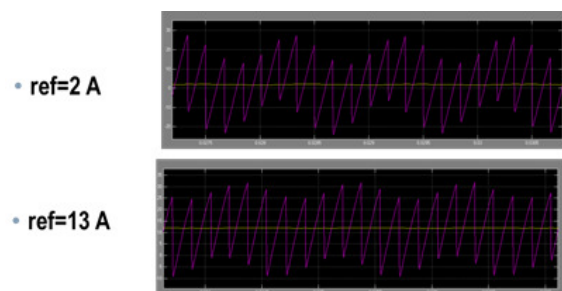


Figure 10: A closed-loop simulation results of current control by proposed rectification method

4 Experiments

The dynamometer of the test platform is an active architecture that includes the torque sensor, single/three-phase power analyser, electronic load and signal measuring instruments and so on. The controller contains a control unit and power unit, the computer kernel is TMS320F280PZ DSP.

At the first of experiment, the virtual hall sensor signals angle will be increased step by step to guarantee the dc link output voltage as expectation. For the 3500 rpm case, the dc link output voltage is 27.88V before modulation by natural synchronous rectifier as left-side of Figure 11; the dc link output voltage is 13.54 V by the proposed rectification method as right-side of Figure 11.

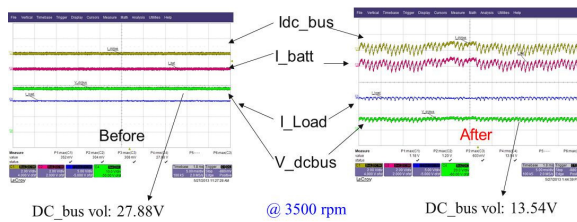


Figure 11: The comparison results at 3500 rpm

From the experimental results, the dc link output voltage will be greater than the battery voltage a lot when the speed is upper than 1500 rpm in this idling stop system. Therefore, the back-EMF voltages had done rectification by the proposed method while the speed is over 1500 rpm in order to guarantee the dc link voltage being fallen within a safe level voltage to charge the battery. The dc link output voltage has a good performance no matter what the speed changes upward or downward in the scooter as shown in Figure 12.

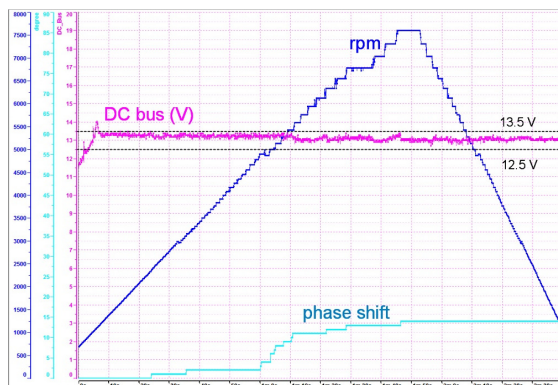


Figure 12: The total performance in the scooter

5 Conclusions

This paper proposes a novel rectification method for a high-level ac voltage conversion to a low-level dc voltage. From the simulation results, the terminal voltage and line current in load-side have a wide convert rate when the internal resistance of battery is of a great value. This research solves the ISG at the higher speed with the back-EMF voltage having a greater battery charging problem in the idling stop system of scooter. Finally, the proposed method has been implemented in scooters idling stop system successfully. As a result, a safe low-level dc voltage can be obtained to charge battery no matter what a variable speed in the scooters, and the power density can reach 1.5kW/L currently.

Acknowledgments

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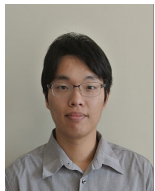
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