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Design and implementation of a low-cost maximization power conversion system for brushless DC generator

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Abstract This paper presents a simple and low-cost method to capture maximum power throughput of permanent magnet brushless DC (BLDC) generator. Conventional methods of rectification are based on passive converters, and because the current waveform cannot be controlled as ideal waveform, a highly distorted current is drawn from brushless generator. It leads to lower power factor and reduces the efficiency and power per ampere capability. So, in this study an active six-witch power converter is employed and based on the phase back-EMF voltage, an optimum current waveform is generated. The phase currents are controlled inphase to phase voltages and their magnitudes are adjusted to regulate the DC-link voltage. Proposed control theory is verified by simulations for BLDC generator and permanent magnet synchronous generator (PMSG). Moreover, some experimental results are given to demonstrate the theoretical and simulation results.
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1. Introduction

Nowadays, developments in distributed generating systems as well as propulsion systems for electric and hybrid electric vehicles have significantly increased the popularity of permanent magnet (PM) brushless generators. These types of generators have been used in various applications such as automotive, micro-turbines, wind power generation, due to their high power density, robustness, and reliability [1]. There are two main types of PM brushless generators: trapezoidal type (BLDCG) and sinusoidal type (PMSG). The PMSGs need high resolution position sensors for optimal operation if the modern vector based control techniques were employed, whereas BLDCGs just need three low-cost Hall-effect position sensors [2]. Compared with other generators, BLDC generator has the advantages of light weight, compact design, easier control, and low maintenance [3,4]. The BLDC generator can have approximately 15% higher power density compared with a PM synchronous generator [5]. On the other hand, due to variable frequency of output voltage caused by variable speed of the generator's shaft in many isolated generation systems such as wind energy conversion systems (WECS) or automotive applications, power electronics interfaces are provided for

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Nomenclature

e_a, e_b, e_c	stator phase back-EMF voltages
H_1, H_2, H_3	output signal of Hall Effect position sensors
i_a, i_b, i_c	stator phase currents
I'_a	reference phase current in negative slope part
L_s	stator inductance per phase
M	stator mutual inductance
P_{avg}	airgap power average
P_{output}	output power of generator
R_s	stator resistance per phase
$t_{H_1,off}$	falling edge instant of sensor H_1
$t_{H_1,on}$	rising edge instant of sensor H_1
$t_{H_2,off}$	falling edge instant of sensor H_2
$t_{H_2,on}$	rising edge instant of sensor H_2
v_a, v_b, v_c	stator terminal voltages
BLDCG	brushless direct current generator
EV	electric vehicle
EMF	electro-motive force
FFT	fast Fourier transformation
HEV	hybrid electric vehicle
PM	permanent magnet
PMDC	permanent magnet direct current
PMSG	permanent magnet synchronous generator
WECS	wind energy conversion system

PM brushless generators. The most important issue in this system is the extraction of maximum electrical power from generator at the lower losses, which reduces the size and weight of the generator [6]. Fig. 1 shows various employed topologies for BLDC generation system.

The simplest solution is the using of uncontrolled three-phase rectifiers as shown in Fig. 1(a) that doesn't need any control and has the lowest cost. In this case, the back-EMF magnitude of the generator must be higher than the DC bus capacitor voltage, which varies because it depends on generator speed and on the DC load. Hence, the output power depends on both speed and load resistance. Therefore, the topology with an uncontrolled rectifier presents relatively low efficiency and low power density [7]. Due to mentioned shortages in some applications, BLDC generators are controlled using diode bridge with DC/DC converter topology as shown in Fig. 1(b). By adding diode bridge to any BLDC generator, different DC/DC converters may be employed with regulation of voltage, current or power. Main reason for

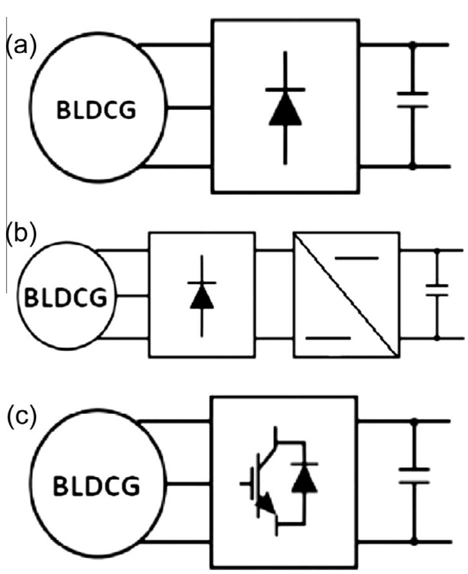

Figure 1 Various BLDC generator topologies (a) passive rectifier, (b) active rectifier and (c) passive rectifier cascaded with DC/DC converter.

exploiting such solution is due to its simplicity and modular design. However, one of the main drawbacks of this topology is highly distorted uncontrolled current in the AC side gives low power per ampere. In this topology, the phase voltages and currents of BLDCG are not inphase, and so the power factor is reduced [8].

Another solution is the use of power converter with six active switches as shown in Fig. 1(c) [9,10]. Various control strategies such as vector based, current waveform shaping and current optimization strategies can be employed for this topology. It seems that this makes control hardware of variable speed generator complex and expensive, but results in outstanding performance for small shaft speeds of the drive. This complex system can be found in regenerative braking applications in electric and hybrid vehicles. On this way, the maximum power per ampere is extracted from BLDC generator [11]. The direct power control strategy has been used for voltage and power regulation of BLDC generator system [12]. In [13] a current control method has been proposed to eliminate torque ripple and maximize power density of non-sinusoidal BLDC machines for EVs and HEVs. On this way, for specific harmonic elimination, a simple algebraic method has been employed instead of FFT. A predictive control of a brushless DC generator based on simultaneously minimization of torque ripple and joule losses has been presented in [14]. A hybrid permanent magnet (HPM) generator has been used at fixed rotor speed passive filter to generate a variable DC-link voltage for hybrid electric vehicle in [15]. The machine excitation is controlled to capture the desired power and voltage. Foregoing problems due to current distortion has been solved with a complex system. Another BLDCG based power supply system using passive rectifier has been used for small-scale WECS in [16], in which for DC-link voltage regulation a DC/DC converter has been used. In [17] a BLDCG based wind energy conversion system for distribute electric power generation has been employed. A PWM rectifier is used for controlling the BLDCG power and the reference phases' currents are as rectangular.

This paper develops analysis and implementation of a new current shaping algorithm for BLDC generator. Developed algorithm can be designed for maximum power extraction or DC voltage regulation. Proposed system may be used for WECS, regenerative braking in automotive systems and micro-turbine based power supply systems. After description

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