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MULTIPORT BIDIRECTIONAL SRM DRIVES FOR SOLAR-ASSISTED HYBRID ELECTRICBUS POWERTRAIN WITH FLEXIBLE DRIVING AND SELF-CHARGING FUNCTIONS

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ABSTRACT:

The hybrid electric bus (HEB) presents an emerging solution to exhaust gas emissions in urban transport. This pa- per proposes a multiport bidirectional switched reluctance motor (SRM) drive for solar-assisted HEB (SHEB) power train, which not only improves the motoring performance, but also achieves flexible charging functions. To extend the driving miles and achieve self- charging ability, photovoltaic (PV) panels are installed on the bus to decrease the reliance on fuels/batteries and charging stations. A bidirectional front-end circuit with a PV-fed circuit is designed to integrate electrical components into one converter. Six driving and five charging modes are achieved. The dc voltage is boosted by the battery in generator control unit (GCU) driving mode and by the charge capacitor in battery driving mode, where the torque capability is improved. Usually, an extra converter is needed to achieve battery charging. In this paper, the battery can be directly charged by the demagnetization current in GCU or PV driving mode, and can be quickly charged by the PV panels and GCU/ACgrids at SHEB standstill conditions, by utilizing the traction motor windings and integrated converter circuit, without external charg- ing converters. Experiments on a three-phase 12/8 SRM confirm the effectiveness of the proposed drive and control scheme.

Keywords: HEB, SHEB, PV system, SRM, SRM drive, AC grid

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INTRODUCTION

In the light of present global energy scenario, there is little doubt that the solution to the world energy issue revolves around the decolonisation agenda, which has created a notable divergence from conventional technologies associated with coal and nuclear to those supporting new market designs, electric storage and digitalisation with renewable energy sources being the centre of focus [1]. Global emissions scenarios studies highlight how transport is responsible for about 23% of total energy-related carbon emissions worldwide, with emissions projected to double by 2050, as suggested by the rapid growth in this sector [2]. Governments across the globe are setting ambitious fuel economy targets to be met in the near future, which presents us with the fact that the future of transport is electric [3]. This is where electric vehicle (EV) technology shows its significance and promises increased energy-security, improved air quality and reduced emission gap. Due to higher efficiencies, electric machines (EMs) are replacing mechanical actuators and machines around the world and the automotive sector is the recently evolving domain where the EM has taken over the role of propulsion device [4]. The desired features of an EM for traction application are a high torque and power density, high torque while starting, wide speed range, intermittent overload capability, high reliability, robustness and reasonable pricing [5]. Switched reluctance motor (SRM) is one of the promising candidates when compared to induction machine, permanent magnet synchronous motor and brushless DC motor due to robust rotor structure and simplicity in construction, lower cost, unipolar converter requirements needing fewer switches with inherent fault tolerance capability and the absence of permanent magnet and brushes and therefore reduced overall production and operational costs [6]. Owing to the unstable prices of permanent magnets, the present research is focused on the development of motors which are rare-earth-magnets free. Switched reluctance machine has been the topic of recent interest in EV applications owing to multiple opportunities towards performance improvement in terms of torque ripple minimisation, better design and advanced control requirements. According to the unidirectional current flow requirement of the machine, a generic asymmetrical half-bridge converter with two switches per phase forms the conventional SRM drive, as shown in Fig. 1. The complete cycle consists of three regions: magnetisation (applying +Vdc), free-wheeling (applying zero voltage) and demagnetisation (applying −Vdc) across the phase. Various converter topologies catering to specific drive requirements are available in the literature. The SRM phase windings are excited using two threephase intelligent power modules (IPM) to achieve improved current response and torque generating capability. Five legs of two three-phase IPMs are used for SRM excitation, whereas one leg is used to form a front-end dc–dc converter. A quasi-three-level converter is discussed in for reducing current rising and falling times but it requires three switches per phase for achieving it. An SRM drive with an integrated charging facility is discussed in for a three-phase SRM but a single switch is shared among three phases for winding excitation and so the performance is deteriorated during the commutation region. A split-converter fed SRM drive for fault-tolerant applications is discussed where the machine features with a centre-tapped winding which is used for charging and driving modes. An integrated multiport converter is formed for solving the requirement of higher capacitance on dc bus by switch multiplexing technique. A tri-port converter is discussed in for power flow among battery PV and SRM to achieve various driving and charging modes. Electromagnetic design consideration of a six-phase SRM fed by the standard three-phase inverter is discussed. A modular power converter formed using a dual and a six-pack IGBT module for a three-phase SRM is presented Where phase windings are Yconnected and bipolar excited. PV panel feeding a canonical switching cell converter front-end is connected to a midpoint SRM converter for solar water pumping application. An integrated multiport converter for reduced ripple bi-directional power flow control is developed where battery current ripple issue is addressed. A multi-level converter for PHEVs is proposed where multilevel voltage during driving mode is achieved using a front-end circuit and

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an asymmetrical converter (ASC) and battery charging is done during stand-still conditions. The last two decades have seen a lot of progress in increasing the efficiency of PV arrays and work towards reducing their cost. A considerable amount of work is done in the area of PV powered drives and is available in the literature but very few are based on integrating grid, PV panel, battery and SRM to achieve various modes of operation using a single converter with a minimum number of switches. An SRM-based multiport bidirectional drive for PV-assisted electric bus is discussed. It employs ASC along with a bi-directional front-end to achieve multilevel voltage for faster demagnetisation. However, the gridto-battery charging mode is not done under a unity power factor (UPF) conditions. Moreover, only two levels of voltage can be produced by the series connection of the generator control unit (GCU) and battery under driving mode. To overcome such limitations, the proposed work is dedicated to create a bidirectional multiport solar-assisted SRM drive (BMSSD) system which integrates and controls the power flow between grid, PV, battery pack and SRM to achieve high dynamic performance of the machine during driving, braking and charging modes by incorporating a minimum number of switches and junction relays. The major objectives covered in this work are

i. Variable dc-link voltage as and when demanded smooth transition from low to high-speed driving is achieved with a single source (battery power) unlike earlier works where specific voltage level was achieved by the series connection of battery pack and GCU (secondary source).

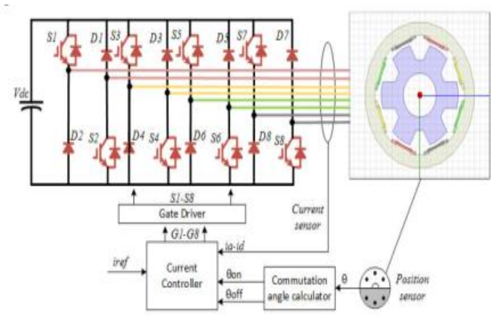
ii. During uphill driving requirements demanding higher power, PV can assist the battery and the equivalent energy source can operate at a maximum power point (MPP) conditions. During light load conditions with sufficient solar irradiance, the PV panel can provide the EV demanded power independently.

iii. The on-board charger formed by the proposed drive offers four charging modes of the battery pack. Under the vehicle standstill condition, the battery pack can be charged by the utility grid at UPF without external equipment. It not only leads to efficient battery charging, but also improves the power quality at the grid side. PV panel can independently charge the battery pack thereby reducing reliance on charging stations. Under downhill running conditions, the regenerative braking energy can be used for charging. Moreover, the demagnetising current during PV only mode can be used to charge the battery pack.

iv. Since charging modes do not involve EV motor winding, it avoids additional control complexities in balancing the winding currents due to unequal inductance in individual phases at different rotor positions. Also, the possibility of vibration or movement of the machine rotor during charging can be completely eliminated.

v. Fault-tolerant control of SRM is proposed and implemented during driving conditions. The machine maintains its performance under loaded conditions when subjected to singlephase open-circuit fault as well as two-phase open-circuit fault thereby confirming the effectiveness of the control strategy.

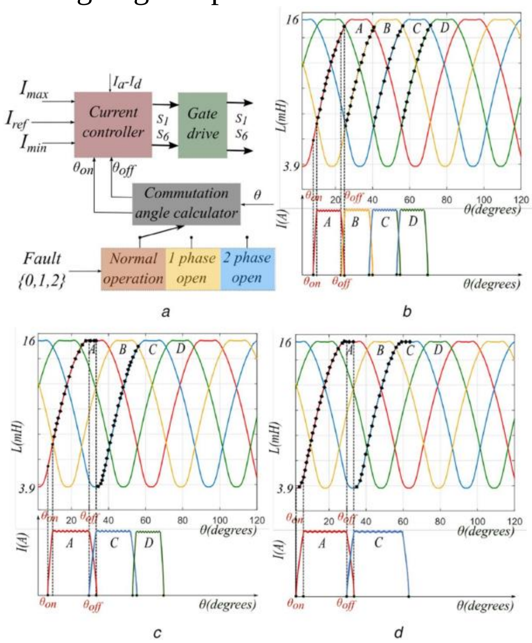
vi. The proposed system possesses the highest functionality index among existing topologies suitable for solar-assisted EV applications, which makes it a strong candidate among multiport systems.



METHODOLOGY

SRM CONTROL IN MOTORING AND BRAKING MODE

SRM phases are excited using the MMSC section of the proposed drive as shown in Fig. Closed-loop speed control of SRM is achieved using an outer speed PI loop, which generates current reference. The reference current is compared with the actual phase currents and the error is processed by a hysteresis current controller to generate switching pulses for MMSC corresponding to the turn-on, turn-off angles decided by the commutation angle control block. The commutation angles are calculated depending on the rotor position information derived from an encoder. Forward motoring, reverse motoring as well as braking operation is implemented by controlling the turn-on, turn-off angles corresponding to the ascending and descending inductance profile of the machine, respectively. Due to the doubly salient nature of SRM, its operation requires each phase to be magnetised and demagnetised such that flux should return to zero within each cycle. At lower speeds, demagnetisation is achieved easily, as the back-emf is low. But at higher speeds, the back-emf increases and it becomes difficult to demagnetise the phase with the same voltage. However, increased voltage level during high-speed operation through our topology, aids in demagnetising the phase quickly and leads to improved torque profile. According to the mode of operation-low speed or high- speed driving, the dc-link voltage can be controlled from 0 to 72 V for low-speed operation and from 72 to 150 V for high-speed operation. The Vdcref is governed by the speed requirement during the driving mode. The switched reluctance drive is known to be more fault-tolerant than other drives, mostly because it can continue operating and produce torque with one or more of its phases not functioning. However, the performance changes under faulty conditions. A fault-tolerant control strategy is proposed and implemented to run the machine at desired operation conditions under normal and faulty conditions when either one phase or two phases are undergoing an open-circuit fault.



BATTERY CHARGING CONTROL

The EV battery is charged at stand-still conditions using the power from the ac grid at unity pf or the installed PV panel at MPP with the help of on-board charging infrastructure. The advantage of the proposed converter while charging from the grid is that it can be fed directly from single-phase ac supply and utilises the freewheeling diodes of

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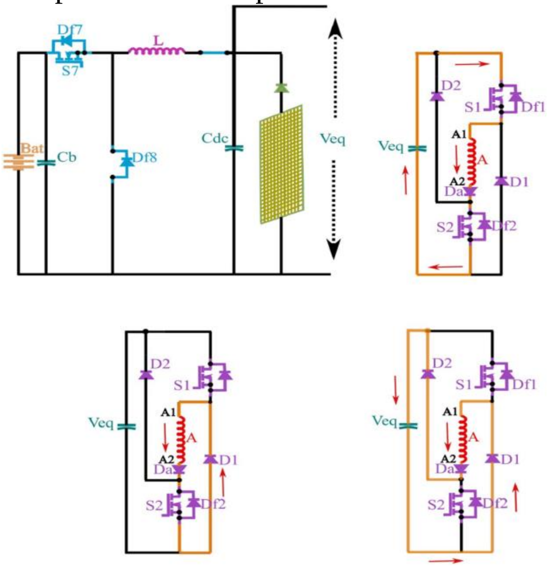
alternate phases to form an onboard rectifier along with the front-end circuit to achieve PFC charging. Charging from PV can be achieved at MPP by using the front-end circuit to regulate the battery charging current. The PV array power is tracked and maintained at MPP using an incremental conductance algorithm which takes into consideration the fact that the slope of PV array power curve becomes zero at the peak power condition and positive and negative to the left and right of MPP point, respectively. Since charging modes do not involve EV motor winding, it can avoid additional control complexities in balancing the winding currents due to unequal inductance in individual phases at a particular rotor position.



Regenerative braking during vehicle downhill motion

When the EV undergoes a downhill motion, the power demand of the machine reduces because the downward motion is facilitated by the gravitational forces and there is a need to limit the speed from overshooting its desired value. Relay $J1$ is open while $J2$ is closed as the machine is excited using a PV array. SRM is operated under regenerative braking mode by shifting the pulses to falling inductance profile of the machine and transferring the regenerated power to the battery pack. This can be achieved in buck/boost modes according to the requirement. The boost mode will charge the battery pack to its nominal voltage and buck mode (auxiliary battery charging) for low voltage dc loads on EV

CONCLUSION

In this project, a multiport bidirectional SRM drive is proposed for SHEB applications, which not only improves the motor sys- tem performance in running conditions, but also achieves flexi- ble charging functions. Multiple driving and charging modes are achieved. Multilevel voltage is obtained to increase the torque capability. PV panels are installed on the bus to extend the driving range and achieve self-charging ability. Correspond- ing working modes and control strategies are investigated in detail. The main contributions of this paper are as follows.

A simple multiport bidirectional SRM drive is designed to combine the GCU, battery bank, PV panels, and SRM for flexible driving and charging functions, by using fewer power devices. The charging functions can be directly achieved by the motor windings and converter circuit.

Six driving modes are achieved. When the solar irradiance is not sufficient, the SHEB can work in the GCU driving mode, pure battery driving mode, and GCU-battery driv- ing mode, according to the running conditions. When the solar irradiance is sufficient, the PV can work with the battery/GCU together as an assisted sustainable energy source to contribute to the motor driving, which signifi- cantly reduces the reliance on fuels/batteries. In addition, in downhill motoring condition, the PV can provide

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the energy independently to drive the motor.

Five charging modes are achieved without external charg- ing converters. The battery bank can be slightly charged by the demagnetization current in the GCU driving mode and PV driving mode. During the braking progress, the energy can be recycled to the battery. Furthermore, the battery bank can be quickly charged by the PV pan- els, GCU, or ac grids at SHEB standstill condition, whichreduces the reliance on charging stations. Corresponding control strategies are presented to achieve the flexible en- ergy control.

The dc voltage is boosted and multilevel voltage is achieved by the battery bank in the GCU driving mode, and by the charge capacitor in the pure battery driving mode. The excitation and demagnetization processes are both accelerated due to the boosted dc voltage. The torque capability can be increased by 35% due to the multiport topology without torque ripple increase.

Although the paper has targeted electrified vehicle appli- cations, the developed technology can be applied to other high-torque and high-speed applications, such as more-electricaircraft, traction drives, and electrical ships.

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