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Power Conditioning System for Electric Vehicle Using Space Vector Modulated Inverter

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Abstract: This paper proposes the use of space vector pulse width modulation instead of six pulse width modulation. Efficient power conversion technologies are strategic to the advancement of battery based vehicles. Two level power conversion topologies (hybrid modulation technique) to obtain variable ac from the battery are proposed. The switching of the power devices are based on the proposed hybrid modulation technique that minimizes the switching losses in the inverter. Converters do not use the dc-link filter capacitors. Elimination of the dc-link capacitor not only reduces the size and volume but also helps in retaining the sine wave modulated information at the input of a three-phase inverter.

Key words: Electrical vehicles (EVs) · Power conditioning · Propulsion

INTRODUCTION

Auxiliary energy storage is required for start-up and storing energy captured during regenerative braking. One way to accomplish this is to place a battery or an ultracapacitor of enough capacity with a bidirectional dc/dc converter. This auxiliary supply also meets the quick change in propulsion load requirement that cannot be supplied by fuel cell stacks [1, 2, 3].

A dedicated study and comparison evaluation is needed for new power conditioning systems (PCSs) with new materials and devices along with the fuel cell stacks available from several manufacturers of identical power levels [4, 5, 6, 7]. This brings up certain new possible system architecture along with new power electronics system and control. It may be novel in terms of lower cost and space requirements (compact system) along with reduced complexity of power electronics system and control [8, 9, 10].

Design of compact vehicles with a high-efficiency power system is of significance to the customers as well as to the automotive industries. The objectives of this paper are 1) to propose, study and select efficient FCV power conditioning architecture for propulsion and 2) to develop switching and control strategy to reduce the power losses and, hence, to reduce the size of the PCS. In this direction, [11, 12] efforts have been put forward in proposing novel topologies and modulation techniques to improve efficiency and size.

This paper is also proposing a novel six-pulse modulation (SPM) followed by 33% modulation to produce three-phase ac waveforms through a single reference with low total harmonic distortion (THD) for induction motors. Thirty-three percent modulation reduces switching losses by at least 66% and SPM avails soft switching over wide dc bus voltage variation and reduces switching losses significantly. Thus, these two modu-lations functioning together at 100 kHz presents high efficiency while achieving compact and lightweight designs, which are of important concern for a vehicle design.

Topologies of Electrical System: Various PCSs for FCVs such as single-stage three-phase inverters, *Z*-source inverters, etc., have been proposed in the literature. Although these are very simple to realize, cost effective and reliable topologies, there is no galvanic isolation between fuel cell, battery and motor drive. Moreover, functioning of the system for wide variation in fuel cell voltage of 100% with load current variation has not been reported in the literature. In a more sophisticated architecture, a battery or an ultra-capacitor of enough capacity is placed as an auxiliary source of energy, as shown in Fig. 1. A high-voltage variable dc bus voltage of either 255–425 V [13], [14] or 150–300 V [15] has been proposed, which is obtained from the fuel cell stack. A bidirectional dc/dc converter is used to boost 12 V to match the dc-link voltage and three-phase inverter to the drive traction motor from the dc link.

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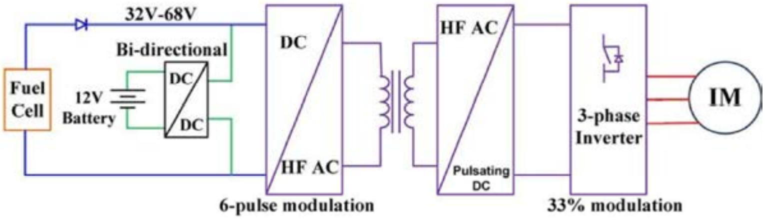

Fig. 1: FCV power system architecture with a low-voltage variable dc-link voltage

During cold start, a bidirectional dc/dc converter boosts 12 V from the battery to a desired high voltage to start the fuel cell. As soon as the fuel cell is started, the battery can be charged using the bidirectional power flow property of the converter. During regenerative braking, energy from the motor drive is put back into the battery. The battery also assists the fuel cell during a sudden increase in load demand such as acceleration of the vehicle.

The challenges in this topology are the design of an efficient and compact bidirectional dc/dc converter to boost from 12 V to a higher variable voltage and maintaining high efficiency at low THD of a three-phase inverter whose dc-link voltage is varying from 150 to 300 V.

In the architecture shown in Fig. 1, an additional dc/dc con-verter has been used to obtain a fixed dc bus voltage from a vari-able voltage of a fuel cell stack. This supplementary converter may increase the component count and size of the overall sys-tem, but design and control of the bidirectional battery charger and inverter are easier compared with previous topologies. The fuel cell converter has its input varying between 32 and 68 V and a fixed output voltage of 100 V. The bidirectional converter needs to boost 12 V from the battery to a fixed output voltage. Since the voltage gain of the converter is relatively constant, it is easier to design a converter having maximum efficiency at this operating condition. Constant dc voltage simplifies control of the three-phase inverter and traction drive.

Power Electronics Topologies

High-Voltage Variable DC Bus Architecture: The architecture shown in Fig. 1 involves a bidirectional dc/dc converter to boost 12 V from the battery to a variable high voltage of 150-300 V and three-phase inverter.

Battery voltage needs to be boosted to more than 25 times to match the variable fuel cell voltage of 300 V, which is not possible without an HF transformer. A transformer isolated boost converter is one of the suitable topologies. As the output voltage of this converter varies by 100%, it is very challenging to design a converter that can boost 12 V to this voltage as well as to maintain high efficiency and performance throughout the wide variation in operating conditions. Power flow into and out of the battery needs to be controlled, maintaining stability and performance. A snubberless naturally clamped bidirectional current-fed half-bridge isolated dc/dc converter is proposed. The proposed converter achieves zero-current switching (ZCS) of the semiconductor devices on low-voltage-side devices and ZVS of the high-voltage-side devices. Sec-ondary modulation on the high-voltage side suggested in this clamps the voltage across the primary-side devices (low-voltage side) naturally and eliminates concern of switch turnoff voltage spike with ZCS without any additional circuit. It maintains soft switching of all the devices as well as natural or zero current commutation of body diodes of the devices (both primary and secondary) for full variation in a high-voltage bus.

Low-Voltage Variable DC Bus Architecture: In this power system architecture, a low-voltage variable dc bus is used instead of a high-voltage variable bus. The battery has been interfaced with this link by boosting 12 to 32-68 V using a bidirectional dc/dc converter, as shown in Fig. 2. The traction drive is fed from a two-stage HF inverter consisting of a front-end dc/dc converter to produce HF pulsating dc voltage consisting of a six-pulse waveform, on average, through SPM followed by a three-phase inverter switched using the 33% modulation scheme.

A transformer isolated bidirectional boost converter is fa-vored to interface the 12-V battery with the low-voltage dc bus. A challenge in the design of this converter is to have a flat efficiency curve throughout wide variation in the dc bus voltage of 32–68 V. The topologies discussed in previous architectures (Figs. 4-6) are also applicable in this case, except that the boost ratio has come down due to lower dc bus voltage.

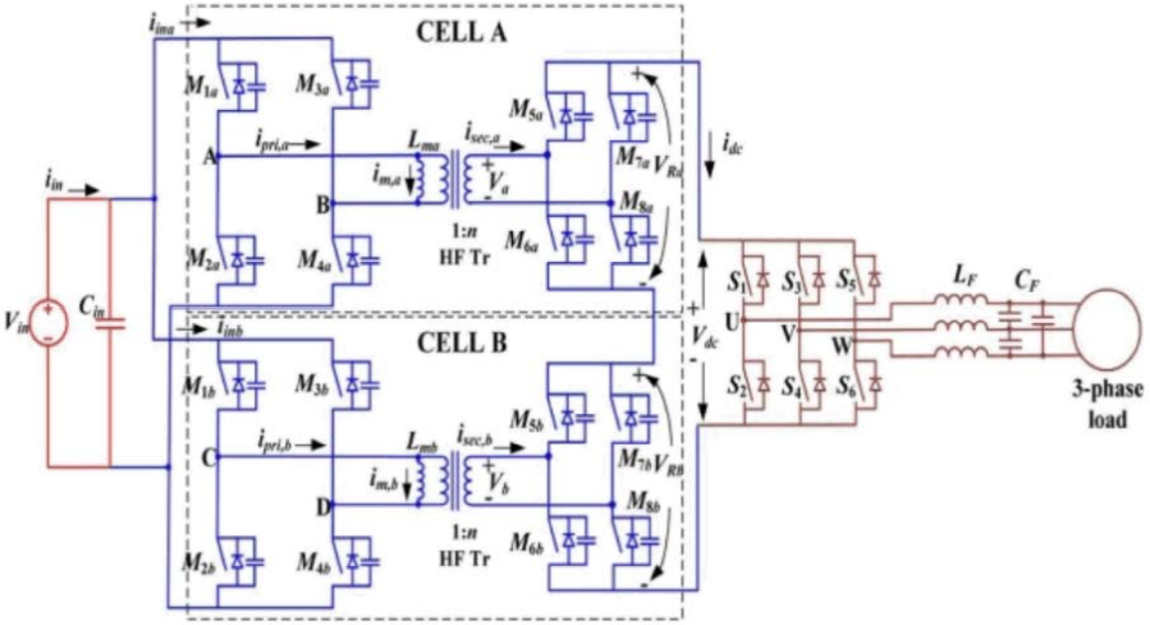

Fig. 2: Schematic of the proposed six-pulse modulated inverter system

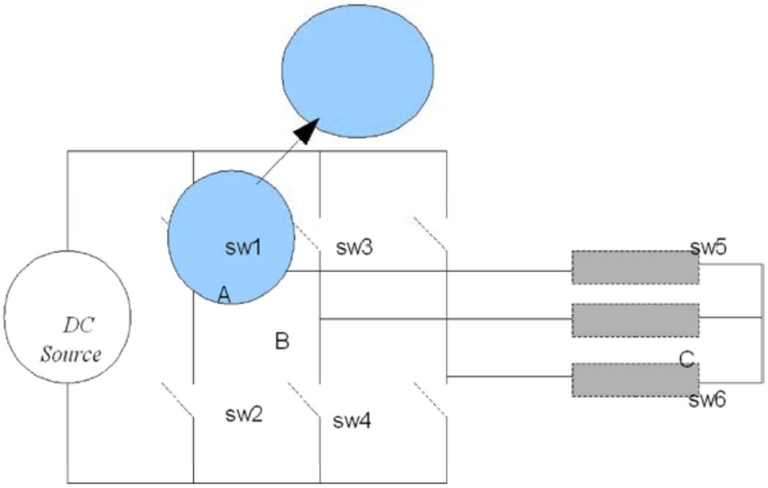

Fig. 3: Three-level three-phase inverter, with a load and neutral point

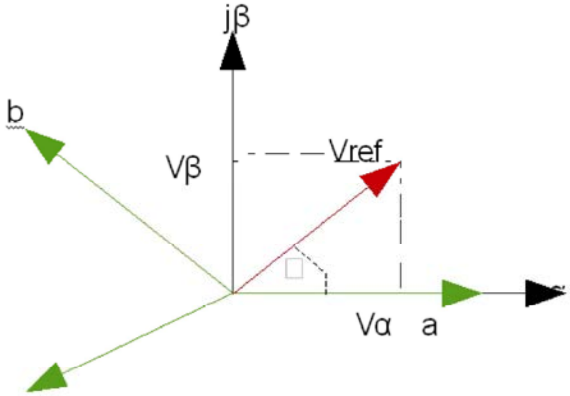

Fig. 4: The reference vector in the two and three dimensional plan

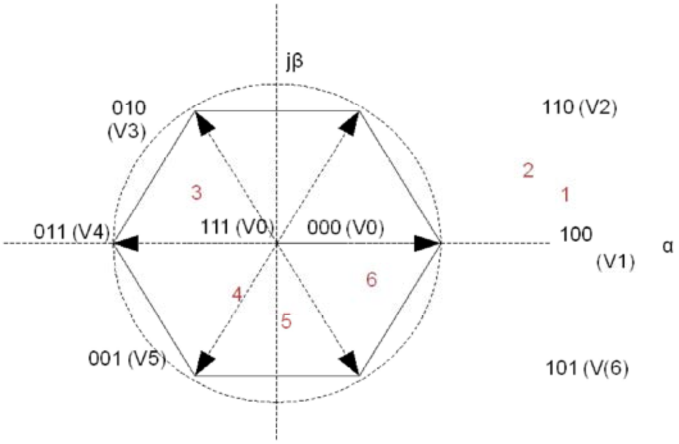

Fig. 5: Space voltage vectors in different sectors

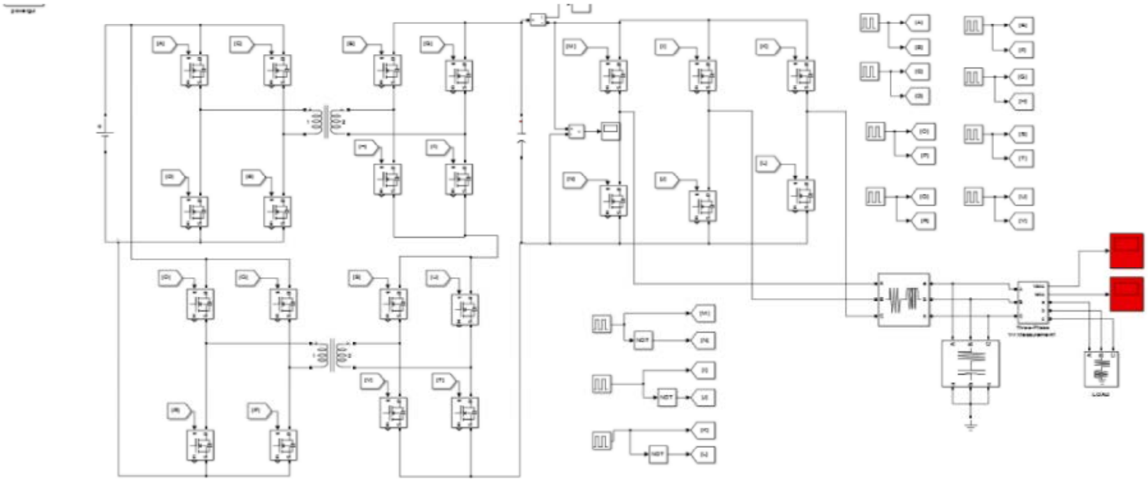

Fig. 6: Simulation model

A single-stage inverter is the simplest possible topology with the least component count. Since the input dc voltage is lower than the peak value of the required output voltage, the voltage needs to be boosted. Therefore, a two- or multistage inverter consisting of a front-end dc/dc converter followed by a standard three-phase pulsewidth-modulation (PWM) inverter is a potential solution. A hybrid modulation technique consisting of two different modulation techniques for a two-stage power converter has been proposed, where the requirement of an electrolytic capacitor at the dc link has been eliminated. In the initial stage, a voltage-fed full-bridge converter is used to produce a high-frequency pulsating dc voltage, which contains a six-pulse waveform, on average, in it. This pulsating dc is fed to a three-phase inverter switched using the 33% modulation technique that gives a balanced three-phase voltage by switching only one leg out of three at any given time.

In a novel single-reference six-pulse modulation technique, two full-bridge converters are modulated using identical six-pulse waveforms producing the output of the pulsating dc voltage at V_{dc}, which is fed to the standard three-phase inverter system. Switching of both the converter and the inverter is modulated in such a way as to reduce switching losses at the inverter and removing necessity of the dc-link capacitor. In case of failure of one of the cells, the inverter can still deliver at least lower power to the motor drive due to unique single-reference control. Since both cells are controlled by a single identical reference, the problem of circulating current has been eliminated.

In the new proposed modulation scheme, the duty ratio is generated from V_{ref}, which is a six-pulse waveform that is obtained from the rectified output of the three-phase line–line voltage.

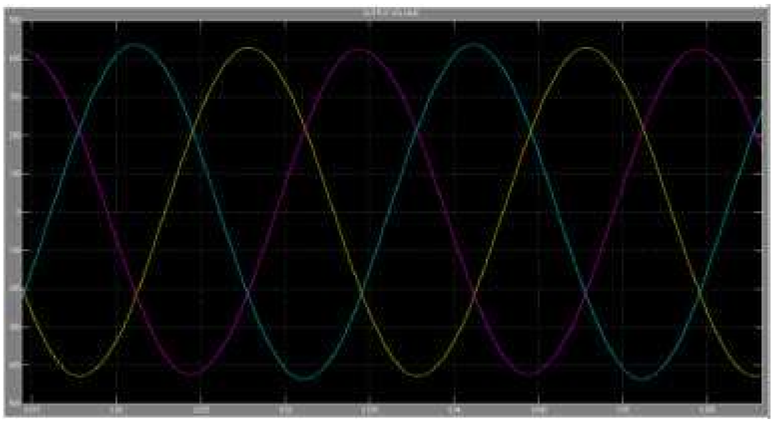

Fig. 7: Output voltage waveform of proposed system

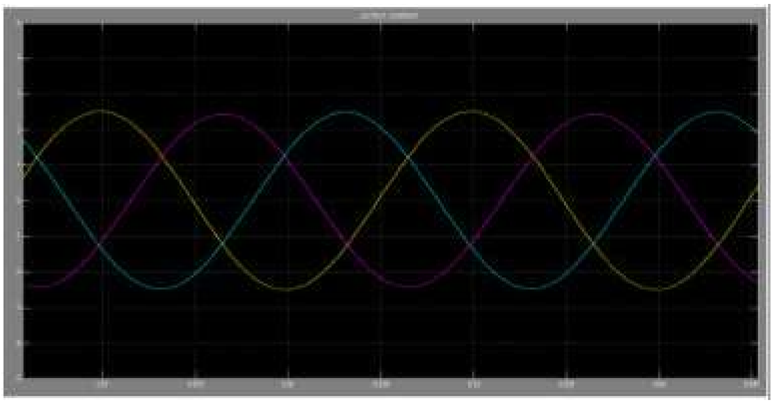

Fig. 8: Output current waveform

During each of these six subintervals, only one out of the three legs of the inverter is being switched at high frequency, whereas the remaining two legs of the inverter are being retained at one switching state. In a complete line cycle, each semiconductor device is switched at high frequency only for one third of the time period. It is also important to note that devices do not commutate when current through them is at its maximum value. This further reduces the switching losses to less than 33%. The drop in switching loss accounts to be around 86.6% in comparison with a standard voltage source inverter (VSI) switched using sine PWM. Once the pulsating dc voltage is switched by the semiconductor devices of the inverter, the volt-age is filtered to obtain a three-phase sine voltage.

Space Vector Pulse Width Modulation for Two-level Converters: The circuit demonstrates the foundation of a two-level voltage source converter. It has six switches (sw1-sw6) and each of these are represented with an IGBT switching device. A, B and C represents the output for the phase shifted sinusoidal signals. Depending on the switching combination the inverter will produce different outputs, creating the two-level signal. The biggest difference from other PWM methods is that the SVPWM uses a vector as a reference. This gives the advantage of a better overview of the system.

Reference Vector: The reference vector is represented in a $\alpha\beta$-plane. This is a two-dimensional plane transformed from a three-dimensional plane containing the vectors of the three phases. The switches being ON or OFF is determined by the location of the reference vector on this $\alpha\beta$-plane.

Table 1 shows that the switches can be ON or OFF, meaning 1 or 0. The switches 1, 3, 5 are the upper switches and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (V_a, V_b, V_c) is positive ($+V_{DC}$). If the upper switches are zero, then the terminal voltage is zero).

The lower switches are complementary to the upper switches, so the only possible combinations are the switching states: 000, 001, 010, 011, 100, 110, 110, 111. This means that there are 8 possible switching states, for

Table 1: Switching states for each phase leg

	a			*b*			*c*		
Switching states	S1	S2	^{v}an	S3	S4	^{v}bn	S5	S6	^{v}cn
1	ON	OFF	^{v}DC	ON	OFF	^{v}DC	ON	OFF	^{v}DC
0	OFF	ON	0	OFF	ON	0	OFF	ON	0

which two of them are zero switching states and six of them are active switching states. These are represented by active (V_1-V_6) and zero (V_0) vectors. The zero vectors are placed in the axis origin (Fig. 18). represented as one rotating voltage vector. There are several different types of multilevel converters on the market and the most studied converters has been described in this chapter: Cascaded H-Bridge When the three phase voltages are applied to a AC machine a rotating flux is created. This flux is Multilevel Converters, Flying Capacitor Multilevel Converters and Diode Clamped Multilevel Converters Choosing the right converter it is important to consider the voltage level to implement. High-level converters gives low distortion but higher voltage unbalance, so there has to be a compromise between those two factors, but also other issues such as increase of equipment for higher levels. For high-voltage high-power applications the inverter also can be used as a control for the voltage and reactive power regulation. This is done when the inverter is connected to a RL-load, a current controller. Designing the multilevel application a software directly connected will be used for this project.

RESULTS

Performances of few of the converters discussed in the previous section are presented in this section. The detailed mathematical steady-state analysis, modes of operation with equivalent circuits, design and implementation are reported i. Experimental results for bidirectional current-fed converter.

The output voltage and current waveform of our system is shown below.

CONCLUSION

This paper reviews various electrical power system architectures for the propulsion system in EVs. Three PCS architectures have been discussed based on the requirements from the aspects of battery storage and propulsion drive system. For these chosen architectures, suitable power converters available in the literature have been discussed with their pros and cons.

In a high-voltage variable dc bus system, only a bidirectional dc/dc converter to interface a battery and a three-phase inverter has been used. It is observed that in order to simplify the control and design of power converters to meet the system requirements, more power converters are essential.

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