MOTOR DRIVES FOR HYBRID ELECTRIC VEHICLES BASED ON CASCADED H-BRIDGE MULTILEVEL INVERTER

By Jinfeng Li

BEng Electrical and Electronic Engineering

Under the guidance of

Dr Pietro Tricoli

University of Birmingham

UNIVERSITY OF BIRMINGHAM

PROJECT BACKGROUND AND OBJECTIVES

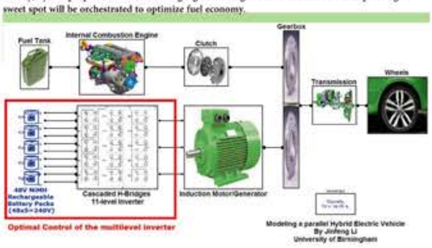
The emerging multi-level inverter outmaneuvers the traditional dual-stage 2-level inverter by the superposition of many smaller voltage steps to synthesize into a desired voltage in staircase nearly sinusoidal even without filtering. The modular structure and transformer-free topology of cascaded H-Bridge multi-level inverter could operate at fundamental switching frequency with low voltage change rate and less susceptible to electro-magnetic interference. Specifically, cascaded H-Bridge multi-level inverter is a natural fit for hybrid electric vehicle drives due to its fault tolerant capability as well as the high performance in manipulating both electric motor drives and energy recovering to recharge the separate batteries during regenerative braking.

The project aims to provide an optimized control strategy for cascaded H-Bridge multi-level multi-cell inverter applied to motor drives for hybrid electric vehicle by considering the following prospects:

(1) Staircase output voltage waveform approaching sinusoidal, with minimized harmonic distortion even without using filter
(2) Fundamental frequency switching, which mitigates the switching loss
(3) Energy balancing between separate DC sources, which prolongs the lifetime of the battery pack and hence reduces maintenance cost
(4) Switching loss balancing between switches in different bridges
(5) Minimized number of DC sources
(6) Minimized number of semiconductor switches
(7) Improved DC voltage utilization
(8) Fault tolerant capability

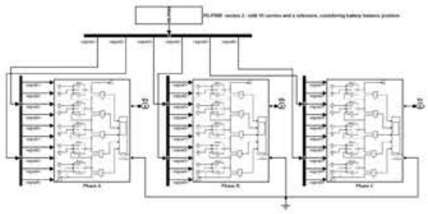
Specifically, Multi-carrier PWM, Selective Harmonic Elimination PWM, modified multi-carrier PWM and several hybrid versions will be designed and simulated to come up with an optimal control scheme for the symmetric cascaded H-Bridge multi-level inverter. After that, the project will extend the symmetric inverter topology to asymmetric case and conduct a comparative study.

At last, the project will apply the aforementioned inverter design into parallel hybrid electric vehicle drives. The control of the multi-level inverter is expected to manage the variable frequency adjustable speed electric motor drives as well as the energy recovering during regenerative braking. Finally, hybrid propulsion drives blending a gasoline engine with an electric motor operating at sweet spot will be orchestrated to optimize fuel economy.



MODELING SYMMETRIC CASCADED H-BRIDGE 11-LEVEL INVERTER

Layout of the 3-phase cascaded H-Bridge 11-level inverter and the control block:



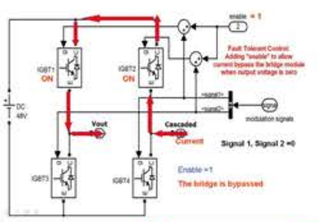
Modular concept

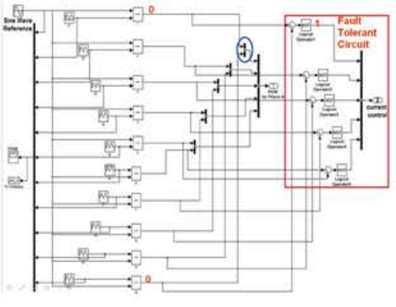
Several identical arrangements of IGBT-based H-Bridges are connected in series to reach the desired voltage output and in parallel to reach the desired number of phases.

In the project, 5 identical battery modules, 48V for each, are connected in series to synthesize 240V phase-to-neutral output voltage. The output voltages and currents are sufficiently close to sinusoidal without using bulky filters.

Fault tolerant design

One of the highlights of the project lies in the fault tolerant design for the cascaded H-Bridge inverter by adding an 'enable' control signal to the upper IGBTs, which ensures that current can circulate normally without conflict when the bridge module is blocked.



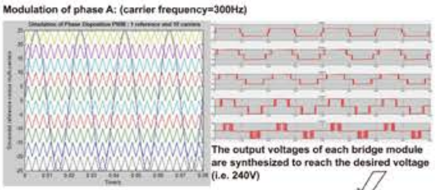


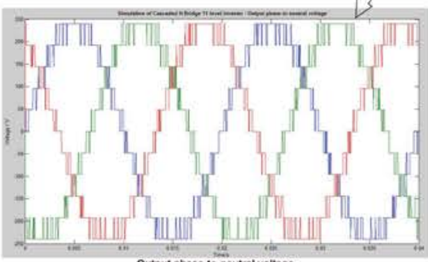
DESIGNING OPTIMAL CONTROL STRATEGIES FOR THE MULTI-LEVEL INVERTER

As the performance of a multi-level inverter (such as harmonic distortion, switching loss and the number of DC sources required) are predominantly dictated by the modulation scenarios, the project conducts a comparative study between diverse modulation control schemes. Multi-carrier PWM and Selective Harmonic Elimination PWM are employed in comparison to the traditional hard-switched two-level PWM. To be more specific, several alternative or modified multi-carrier PWM techniques as well as hybrid versions are proposed for the sake of inverter performance optimization. Modeling and simulation of motor drives based on cascaded H-Bridge eleven-level inverter with 15 modulation schemes are implemented and verified by Matlab/Simulink.

Scenario 1: PD-PWM with 1 sinusoidal reference and 10 triangular carriers in phase

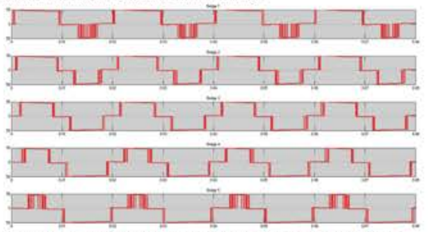
Modulation of phase A: (carrier frequency=300Hz)





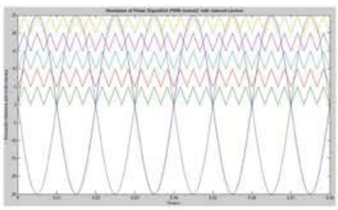
Output phase-to-neutral voltage
(11-level , nearly sinusoidal, without using filter)

Scenario 2: Modified version of scenario1, with an improvement on the energy balance between battery modules of different bridges



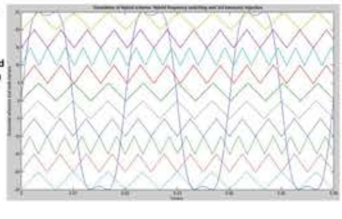
The defect of scenario 1 lies in the unbalanced conducting time of different H-Bridge modules. The battery within the module with a longer conducting time will deplete faster and vice versa. The unequal energy distribution between different battery modules will give rise to a frequent replacement of battery pack, resulting in a rise in maintenance cost.
Scenario2 introduces a swapping conducting scheme. With this cost-effective arrangement, the duty cycle of each bridge is approximately balanced, which indicates that the depleting rates of different battery modules are identical, thus obviating frequent replacement.

Scenario3: PD-PWM with 1 sinusoidal reference and its inverse, with reduced carriers

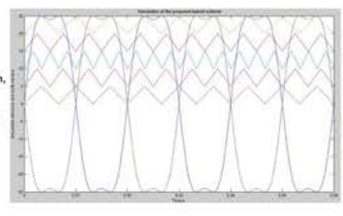


Scenario 4: PD-PWM with 1 sinusoidal reference and its inverse, with 5 inverted sinusoidal carriers
Scenario 5: PD-PWM with hybrid frequency switching
Scenario 6: PD-PWM with third harmonic injection and reduced carriers
Scenario 7: POD-PWM scheme1
Scenario 8: POD-PWM scheme2
Scenario 9: APOD-PWM scheme1
Scenario 10: APOD-PWM scheme2
Scenario 11: Phase Shifted PWM (PS-PWM)
Scenario 12: Selective Harmonic Elimination PWM (SHE-PWM)
Scenario 13: Hybrid scheme combining SHE-PWM and PD-PWM

Scenario 14: Hybrid scheme: PD-PWM with hybrid frequency switching and third harmonic injection



Scenario15: Hybrid scheme: PD-PWM with hybrid frequency switching, third harmonic injection, reduced carriers and improved battery balancing



COMPARATIVE STUDY ON THE MODULATION SCHEMES

A comparative study on diverse control schemes is conducted in light of the simulation results of the motor drives for hybrid electric vehicle (100HP 50Hz 1484rpm induction motor) :

Control scheme	Total harmonic distortion in phase-to-phase voltage	Total harmonic distortion in stator current	Major harmonic order	Number of carriers(per phase)	DC voltage utilization	Switching loss balance	Battery energy balance
Scenario1	6.91%	3.01%	76	10	69.21%	NO	NO
Scenario2	6.91%	3.01%	82	10	69.21%	NO	YES
Scenario3	9.72%	4.26%	47	5	69.18%	NO	YES
Scenario4	11.01%	5.81%	47	5	70.19%	NO	YES
Scenario5	9.08%	12.21%	29	5	69.62%	YES	YES
Scenario6	6.37%	7.36%	88	10	79.05%	NO	YES
Scenario7	8.36%	5.35%	45	10	69.26%	NO	YES
Scenario8	8.89%	6.39%	45	10	69.38%	NO	YES
Scenario9	9.64%	12.96%	54	10	68.80%	NO	YES
Scenario10	9.47%	7.92%	45	10	68.66%	NO	YES
Scenario11	10.02%	4.36%	13	5	69.74%	NO	YES
Scenario12	5.81%	5.31%	19	5	73.68%	NO	NO
Scenario13	7.61%	2.86%	47	5	81.95%	NO	NO
Scenario14	7.44%	2.15%	23	10	79.91%	YES	YES
Scenario15	7.43%	2.26%	25	5	81.67%	YES	YES

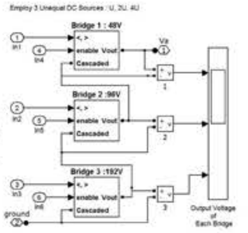
According to the simulation, Phase Disposition PWM (PD-PWM) procures best harmonic spectrum with smaller THD than POD-PWM and APOD-PWM. Scenario2 outmaneuvers scenario1 by realizing energy balance between separate batteries.The scenarios with inverse reference sacrifices better harmonic spectrum to reduce carriers (i.e. reduces controller cost).
Third harmonic injection PWM drastically increases DC bus utilization as proved by Scenario6. Selective Harmonic Elimination PWM functions well in mitigating specified harmonics and achieving the smallest THD.Hybrid switching frequency scheme reduces maintenance cost by improving longevity of the switching devices.
Suffice it to say, the optimized control scenario is a trade off between performance and cost (both from inverter and controller). The hybrid version combining Phase Disposition PWM and third harmonic injection with hybrid switching frequency, reduced carriers and battery energy balancing strategy is proposed and verified.

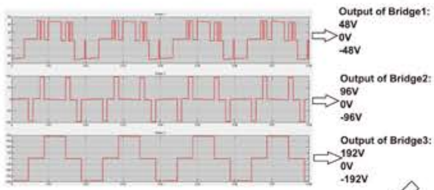
FURTHER STUDY: EXPAND SYMMETRIC INVERTER TOPOLOGY TO ASYMMETRIC CASE

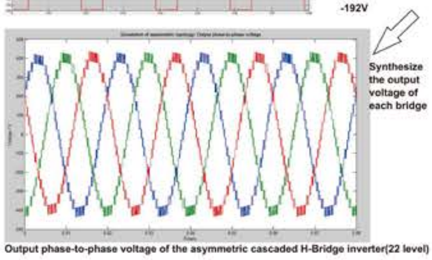
Apart from the aforementioned symmetric cascaded H-Bridge 11-level inverter, which employs 5 equal dc sources each phase to synthesize 11 level voltage output, the asymmetric topology achieves the same output level with a reduced number of battery modules and less semi-conductor switches.

The asymmetric cascaded H-Bridge inverter designed for the project can suffice to synthesize a 240V output phase-to-neutral voltage (11-level) for each phase(or 415V phase-to-phase) by employing just 3 unequal battery modules, i.e.48V, 96V, 192V.

The control strategy for the asymmetric topology is based on Selective Harmonic Elimination PWM.The switching angles are calculated by sovling the non-linear transcendental equations using Newton-Raphson Iterative Method. Correspondingly,the 3rd,5th,7th,11th harmonics have been minimized.



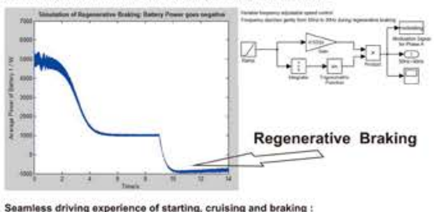




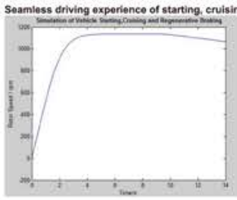
Output phase-to-phase voltage of the asymmetric cascaded H-Bridge inverter(22 level)

MULTI-LEVEL INVERTER APPLIED TO HYBRID ELECTRIC VEHICLE

The simulation of motor drives for a parallel hybrid electric vehicle based on the control of the aforementioned multi-level cascaded H-Bridge inverter functions well.
When the driver pushes the brake button to decelerate the car at the 9th second, the induction motor operates as a generator. The battery power goes negative, which indicates recovering the kinetic energy and converts it into electric energy to charge the battery pack.



Seamless driving experience of starting, cruising and braking :



With the assist of electric motor giving propulsion in parallel, the internal combustion engine (ICE) can always operate around the sweet spot, which optimizes fuel economy especially during city driving.