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Advanced Control Strategy of Bidirectional Converters for Efficient and Low-harmonic Power Conversion in Transportation Electrification

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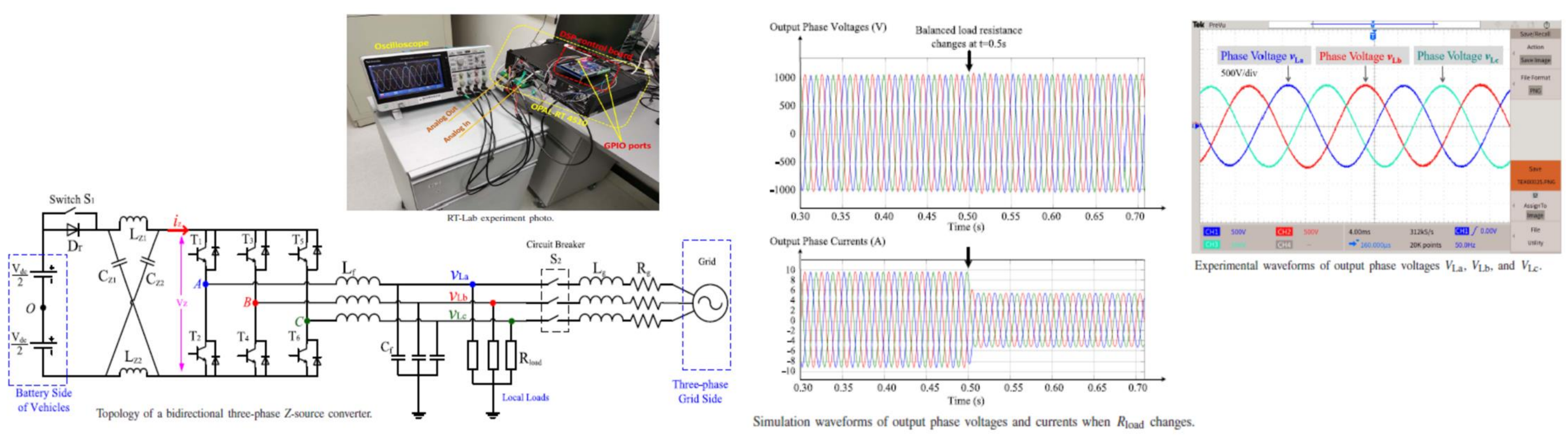
Project Summary

- The enrichment of the key platform of technology for railway electrification systems initiated from the 1st- and 2nd- round CNERC-Rail projects has been implemented in the present project to further enable four more key and advanced control techniques and models of power converters for enabling an efficient and low-harmonic power conversion between electric power grids and transportation (railway) electrification systems with improved power quality and stability.
- These includes:
  1) A low-harmonic control method of bidirectional 3-phase Z-source converters for vehicle-to-grid power transformation;
  2) A dual cost function model predictive direct speed control strategy with duty ratio optimization for permanent magnet synchronous motor drives in electro-magneto-mechanical traction energy conversion;
  3) A short-term prediction of wind energy power and its ramp events based on a semi-supervised generative adversarial network; and
  4) A thermodynamic model of buried transformer substations with underground heat accumulative effect for dynamic loading capability assessment.
- A total of four good SCI journal papers have been published as the direct research output.
- The research results and the acquired knowhow will be applied to and further developed in the on-going RIF project (#R5020-18) and the coming CNERC-Rail project(s).

Low-harmonic Control Method of Bidirectional 3-phase Z-source Converters for Vehicle-to-grid Power Transformation

***IEEE Transactions on Transportation Electrification* 6(2): 464–477, 2020**

- A novel type of 3-phase Z-source inverters for use in transportation electrification systems such as vehicle-to-grid (V2G) chargers is developed to simultaneously provide a solution of voltage boosting by a single-stage topology and a bi-directional operation as a rectifier.
- Three different and new control methods for bi-directional 3-phase Z-source converters are proposed and investigated.
- The best performed one is further developed to a closed-loop proportional-integral control method.
- While the voltage conversion ratio is flexible, the total harmonics distortion of the output voltage is <3% in the voltage ratio range of 0.5–4.0.
- The effectiveness of the proposed method is validated in MATLAB/Simulink simulations and RT-LAB experiments based on the real-time simulator OPAL-RT OP4510.
- The proposed method demonstrates higher performance in harmonics reduction and simpler algorithm with flexible voltage gain in comparison with the existing control methods.



Topology of a bidirectional three-phase Z-source converter

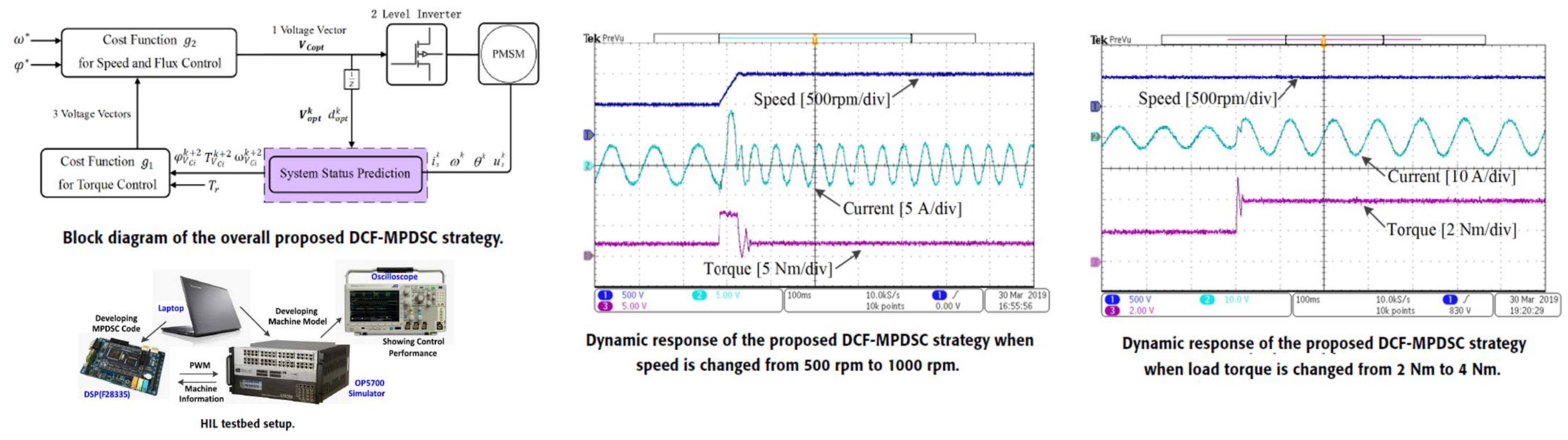
Simulation waveforms of output phase voltages and currents when R_{load} changes.

Experimental waveforms of output phase voltages V_{1a}, V_{1b}, and V_{1c}.

Dual Cost Function Model Predictive Direct Speed Control Strategy with Duty Ratio Optimization for Permanent Magnet Synchronous Motor Drives in Electro-magneto-mechanical Traction Energy Conversion

***IEEE Access* 8: 126637–126647, 2020**

- A new dual cost function model predictive direct speed control (DCF-MPDSC) strategy with duty ratio optimization is developed for permanent magnet synchronous motor (PMSM) drives to improve the total harmonic distortion, torque ripple, speed ripple, and speed offset encountered in traditional cascaded speed loop and proportional-integral regulator-based speed control.
- By employing an accurate system status prediction and based on the deadbeat criterion, the optimized duty ratios between one zero voltage vector and one active voltage vector are deduced.
- Two separate cost functions are then formulated sequentially to refine the combinations of voltage vectors and to provide two-degree-of-freedom control capability.
- The first cost function results in a better dynamic response, while the second one leads to a speed ripple reduction and a steady-state offset elimination.
- The DCF-MPDSC strategy is validated by both Simulink simulation and hardware-in-the-loop experiment to show an excellent control performance of total harmonic distortion 4.43%, torque ripple 0.0423 N·m, speed ripple 0.0121 rpm, and speed offset 0.0055%.
- It has great potential for electric drives and electromechanical traction energy conversion in railway electrification systems to provide a simple and an accurate speed tracking ability.



Block diagram of the overall proposed DCF-MPDSC strategy.

HIL testbed setup.

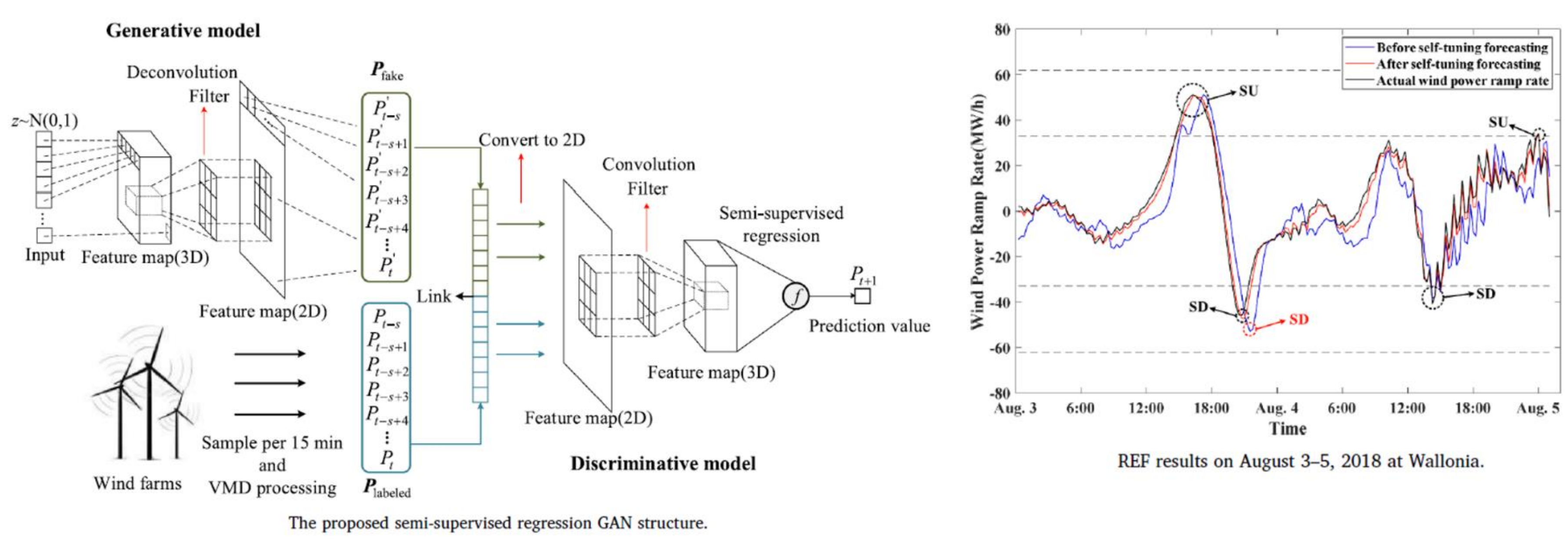
Dynamic response of the proposed DCF-MPDSC strategy when speed is changed from 500 rpm to 1000 rpm.

Dynamic response of the proposed DCF-MPDSC strategy when load torque is changed from 2 Nm to 4 Nm.

Short-term Prediction of Wind Energy Power and Its Ramp Events Based on a Semi-supervised Generative Adversarial Network

***International Journal of Electrical Power and Energy Systems*, 125: 106411, 2021**

- A hybrid forecasting model based on semi-supervised generative adversarial network (GAN) is proposed and validated to solve the short-term wind power outputs and ramp event forecasting problems in relation to the economic operation and risk management of smart electric grids.
- The original time series of wind energy data can be decomposed into several sub-series characterized by intrinsic mode functions (IMFs) with different frequencies, and the semi-supervised regression with label learning is employed for data augmentation to extract non-linear and dynamic behaviors from each IMF.
- The GAN generative model is then used to obtain unlabeled virtual samples for capturing data distribution characteristics of wind power outputs, and the discriminative model is redesigned with a semi-supervised regression layer to perform the point prediction of wind power.
- These two GAN models form a min-max game so as to improve the sample generation quality and reduce forecasting errors.
- A self-tuning forecasting strategy with a multi-label classifier is also proposed to facilitate the forecasting of wind power ramp events.
- The real data of a wind farm from Belgium is collected in the case study to demonstrate the superior performance of the proposed approach compared with other forecasting algorithms.



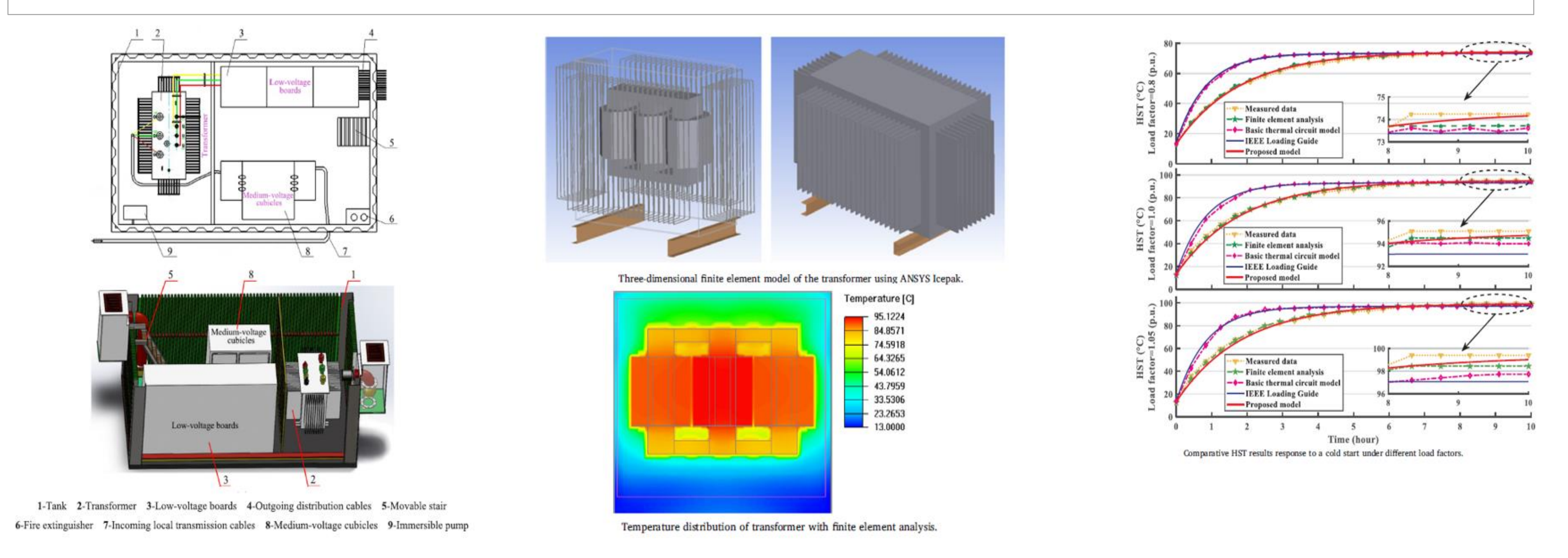
The proposed semi-supervised regression GAN structure.

REF results on August 3–5, 2018 at Wallonia.

Thermodynamic Model of Buried Transformer Substations with Underground Heat Accumulative Effect for Dynamic Loading Capability Assessment

***International Journal of Electrical Power and Energy Systems*, 121: 106153, 2020**

- An extended thermal circuit model for directly buried transformer substations is proposed to dynamically evaluate the transformer loading capability and its lifetime cycle.
- The underground thermal interactions and energy balances among heat generation, transfer and storage in the transformer substation are represented with nonlinear thermal resistances and capacitances based on thermal-electrical analogies, and the hot-spot temperature dynamics can be captured from the nodal analysis on the *R*–*C* thermal equivalent circuit.
- The underground thermal accumulative effect is investigated for dynamic loading capability assessment considering the combined impact of heat accumulation in the surrounding soil caused by fluctuating transformer loads during prior operating periods.
- The finite element analysis with measured data is implemented for parameter tuning and model verification of the proposed thermodynamic model, and numerical simulations confirm the improvements of the proposed model for the transformer life extension and load management.



Three-dimensional finite element model of the transformer using ANSYS Icepak.

Temperature distribution of transformer with finite element analysis.