Novel Hierarchical Transactive Energy Management System Incorporating Predictive Assessment Techniques for Enhanced Community Market Participation

- A short course jointly organized by School of Electrical and Electronic Engineering, NTU and IEEE Singapore Section -

Introduction

Modern power systems are undergoing a transition from conventional to renewable generation, which is considered as an effective way to resolve the global energy crisis and reduce carbon emissions. However, due to the intermittency and variability, the integration of renewable energy sources (RESs) into the utility grid will bring some stability issues. To address these issues, a novel hierarchical transactive energy management system (HTEMS) is proposed. The HTEMS considers distributed energy resources (DERs) which include RESs, energy storage systems (ESSs) and standby generators at commercial and industrial sites. Microgrids can be used as a platform to incorporate RESs, ESSs and generators and validate the proposed HTEMS for monitoring and control of DERs. The proposed HTEMS can enhance their availability, reliability and efficiency.

Since May, 2015, our research team has been working on the Energy Market Authority (EMA) funded project entitled “Novel Hierarchical Transactive Energy Management System Incorporating Predictive Assessment Techniques for Enhanced Community Market Participation”. In this project, a novel microgrid configuration including the model predictive control (MPC) based load frequency control (LFC) strategy with battery storage system, a universal hardware-in-loop (HIL) platform, a flexible power quality conditioner (FPQC) for the power quality improvement, and a multiport three-level cascaded converter (MTLCC) for hybrid energy storage system (HESS) is proposed as shown in Figure 1.

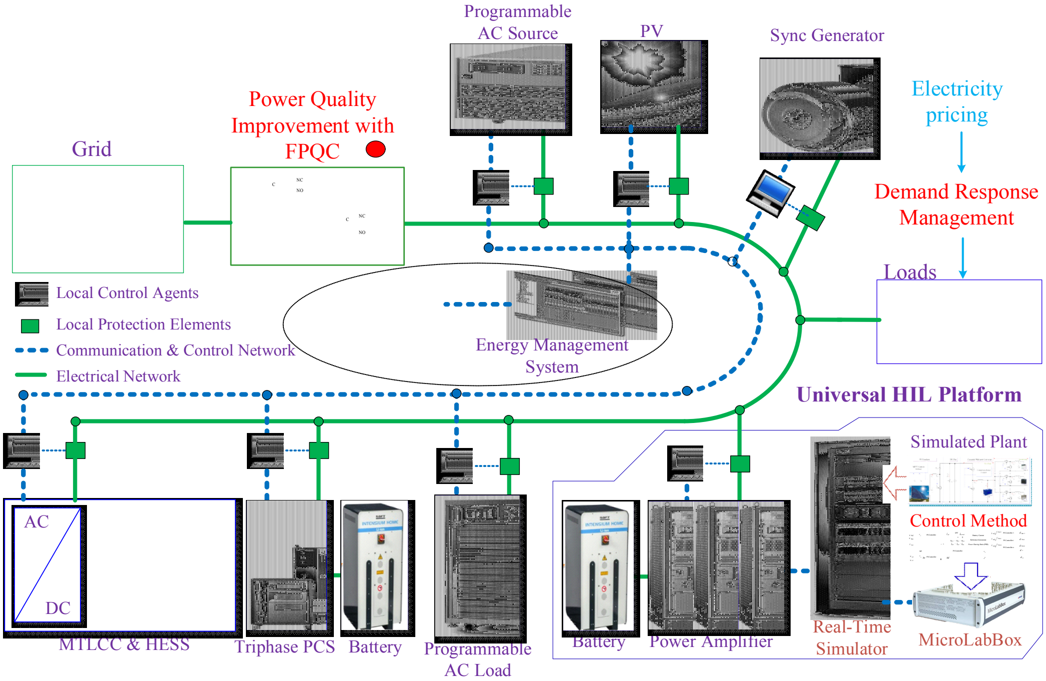


Figure 1. Configuration of the microgrid including the synchronous generator, Triphase PCS interfaced battery system, a universal HIL platform, FPQC, and MTLCC interfaced HESS.

Some salient features of the short course include:

(1) Model Predictive Control (MPC) is the control strategy which has the unique ability to optimize control actions according to a pre-defined objective function by utilizing predicted information, and considering measurable disturbances and system constraints. Moreover, MPC is able to achieve various control targets by deliberately including different variables in the objective function. By using a hierarchical structure, MPC could provide improved system stability and enhances community market participation. In this project, MPC is adopted to regulate the battery energy storage system and eliminate the frequency deviation produced by the power mismatch between power generation and load consumption. A microgrid is setup to validate the MPC-based LFC, as shown in Figure 2. In the short course, the comparison between the conventional proportional-integral (PI) based LFC and the MPC based LFC will be conducted. The results of their performance will be presented.

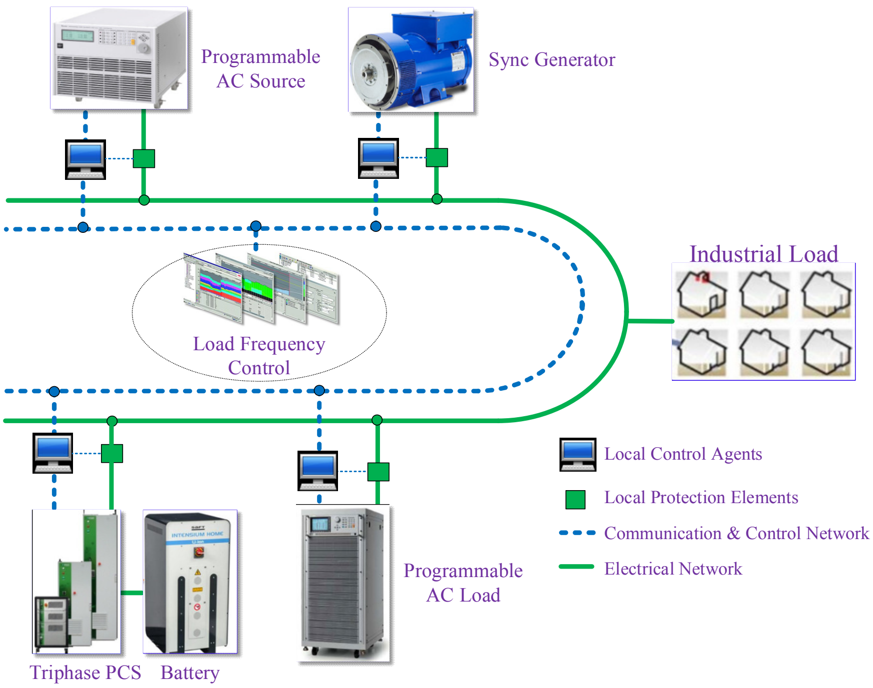
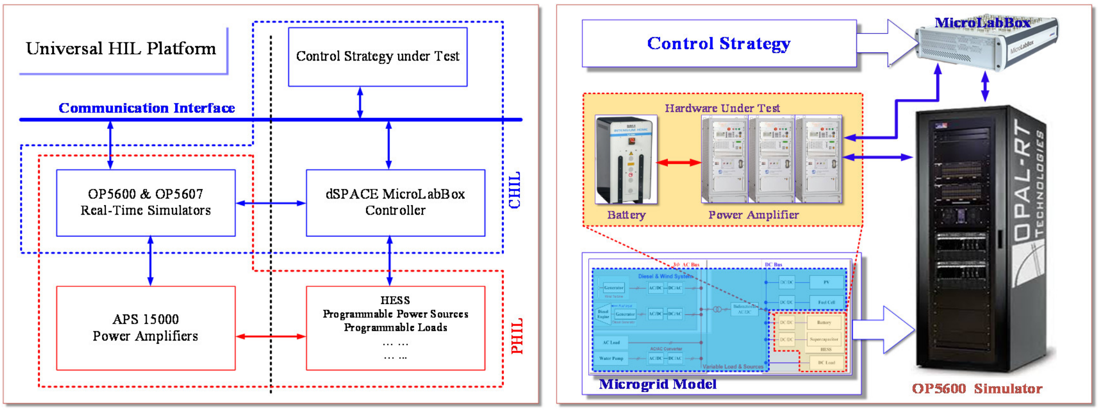


Figure 2. Configuration of the microgrid for MPC-based LFC.

(2) A universal hardware-in-loop (HIL) platform is built based on the Opal-RT OP5600 real-time simulator, dSPACE MicroLabBox controller, Spitzenberger Spies four-quadrant power amplifier and SAFT lithium-ion battery as shown in Figure 3. Short course participants will be introduced to control HIL (CHIL) and power HIL (PHIL) tests for the microgrid. They will learn how to conduct the CHIL and PHIL according to their requirement.

In the CHIL test, the control strategy is implemented in the MicroLabBox controller and the target system is simulated in the Opal-RT simulator in real time. In the PHIL test, the target system is partially implemented in the Opal-RT simulator and the remaining system is implemented by the actual hardware. The hardware under test (HUT) during the PHIL test is integrated with the Opal-RT OP5600 real-time simulator via the power amplifier.



(a) (b)

Figure 3. A universal HIL platform: (a) Block diagram and (b) HIL prototype.

(3) Due to the intermittent nature of the distributed generation (DG) and the various interfaces with power converters, the power quality (PQ) problems, including voltage sag, swell and power factor (PF) decrement, become critical in the microgrids. Particularly, to deliver the same active power when the PF is reduced, the generator needs to generate more power under a low PF and increase the losses of delivery.

To mitigate the PQ problems in the microgrids, the dynamic voltage restorer (DVR) is the most commonly utilized device for voltage compensation. A typical DVR consists of a voltage source converter (VSC) to achieve DC/AC conversion, a battery to supply the DC link of the VSC, a filter to suppress the switching harmonics of the VSC, and a series transformer to obtain the series voltage injection at the distribution line. The use of battery leads to a higher capital and maintenance cost. In the proposed three-phase flexible power quality conditioner (FPQC) as shown in Figure 4, the DC link of the VSC is connected to a parallel converter. Thus, the active power required by the DVR and the power losses to maintain the DC link voltage are supported by the parallel converter. The battery is not needed in the proposed approach. The cost of the proposed FPQC can be lower than that of the DVR system. In addition, a series connected capacitor is also proposed in FPQC to handle the injected voltage so that the series transformer is not required, which further reduces the cost of FPQC. By including the voltage PQ compensation of the DVR, the parallel converter of the FPQC can handle the current PQ problem and PF correction problem when it supports the DC link. Each phase of the three-phase FPQC can be controlled independently. This makes the control of the system more flexible than the traditional DVR system.

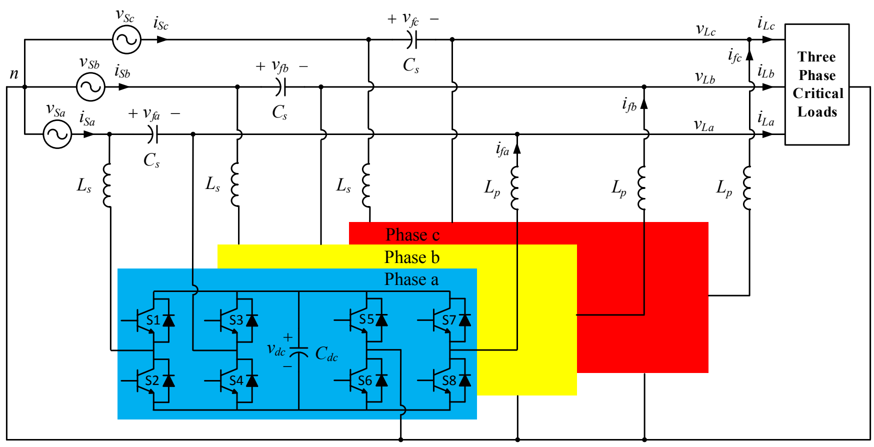


Figure 4. FPQC for power quality improvement with less components.

(4) HESS, which combines batteries of high energy density and supercapacitors with high power density, possesses a superb capability for managing highly fluctuating power demands. Moreover, with the assistance of supercapacitors on compensating the instantaneous power demand, the lifespan of batteries can be prolonged by handling the average power demand. HESS is used to improve the reliability, power quality, dynamic performance, and overall microgrid operating cost.

To integrate the low-voltage HESS into DC microgrids, the conventional solution is allocating each energy storage device (ESD) with one independent full-rating power converter. When the HESS consists of multiple ESDs, it results in a system with high volume, weight and cost. Another issue of the conventional converters for HESS is the availability of only two voltage levels of zero and a full DC bus voltage. It produces a large voltage difference across the converter inductor, which subsequently leads to high current ripples. To compensate for the deficiencies of the existing HESS converters, a MTLCC is proposed for integrating HESS into the DC microgrid as shown in Figure 5. MTLCC enables the integration of multiple ESDs with only one converter. Furthermore, the three-level and cascaded structure of MTLCC reduces the voltage stress on the power switches and inductors so that the rating and size of these components as well as their cost can be reduced. In this short course, the prototype and the operation of the MTLCC will be presented.

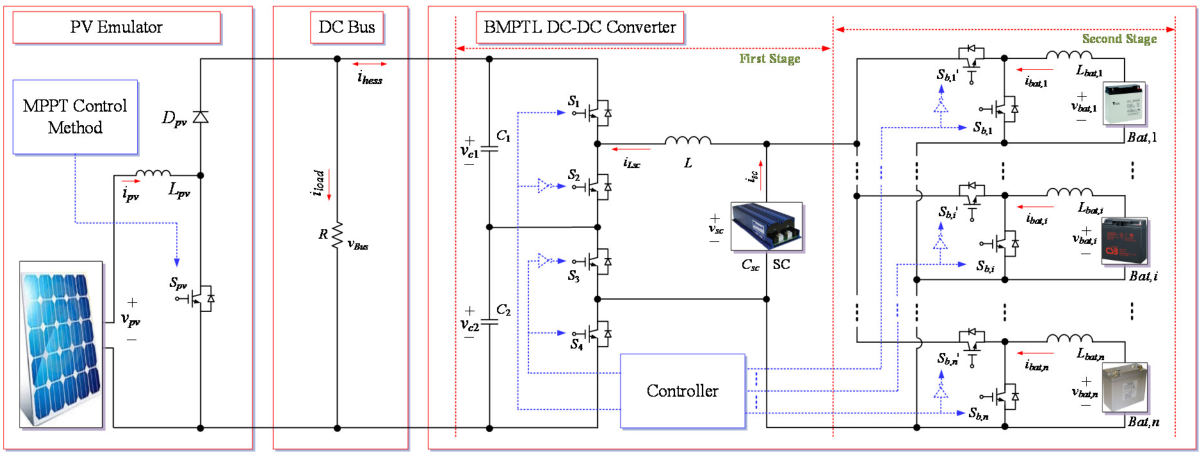


Figure 5. Integration of HESS into DC microgrid with MTLCC.

Hardware and Software Demonstration

Demonstration of the abovementioned technologies using the MPC-based LFC, universal HIL platform, and experimental prototypes of FPQC and MTLCC interfaced HESS in the laboratory.

<u>MPC-based LFC</u>: We will perform the following hardware demonstration:

(a) Demonstration of microgrid operation with a synchronous generator, a lithium-ion battery, a programmable AC source, a programmable load and an industrial load;
(b) Demonstration of the MPC-based LFC; and
(c) Demonstration of comparison between MPC-based LFC and PI-based LFC.

<u>HIL</u>: The CHIL and PHIL concept which is a natural extension of HIL will be introduced. Participants will have an opportunity to view a real-time demonstration of CHIL and PHIL tests on the microgrid testbed at Clean Energy Research Lab (S2-B7c-05) in EEE, NTU. We will perform the following hardware demonstrations:

(d) Explanation of the universal HIL platform;
(e) Explanation of the configurable target system for CHIL and PHIL;
(f) CHIL test using the state-of-art Opal-RT OP5600 real-time digital simulator and an all-in-one dSPACE MicroLabBox controller; and
(g) PHIL test using the OP5600 real-time simulator, Spitzenberger Spies four-quadrant power amplifier, and SAFT lithium-ion battery.

<u>FPQC</u>: Demonstration of the FPQC is done for verifying its voltage and current mitigation capabilities. We will perform the following hardware demonstrations:

(h) Introduction of FPQC configuration and principle of operation;
(i) Demonstration of voltage compensation capability of FPQC; and
(j) Demonstration of current power quality mitigation capability of FPQC.

<u>MTLCC interfaced HESS</u>: We will perform the following hardware demonstrations:

(k) Introduction of MTLCC interfaced HESS configuration and principle of operation;
(l) Demonstration of charging/discharging of the battery/supercapacitor via MTLCC;
(m) Demonstration of energy management of the battery/supercapacitor;
(n) Demonstration of DC bus voltage regulation of the microgrid using HESS;
(o) Demonstration of power sharing between the batteries and supercapacitor; and
(p) Demonstration of power sharing among the batteries interfaced by the MTLCC;

Course Objectives

In this course, four presentations related to the overview of the project, MPC-based LFC, HIL, FPQC and MTLCC interfaced HESS will be introduced. The basic concept, development and principle of these technologies will be introduced in detail. In the demonstration section, the function and effectiveness of the MPC-based LFC will be validated and its performance will be compared with PI-based LFC based on the microgrid in our lab. The hardware configuration, design and implementation of the universal HIL platform, and the self-developed experimental laboratory prototypes of FPQC and MTLCC interfaced HESS will be introduced. The various operating modes and pre-set functions of the universal HIL platform and lab prototypes will be demonstrated to validate the feasibility and practicability of the proposed technologies.

It is expected that through this course, the participants are able to understand the principle of operation, current R&D trend and the challenges of the technologies towards the enhancement of reliability and power quality of the microgrid. In addition, we would share with the participants the design rules and implementation methodology of the proposed MPC-based LFC, HIL, FPQC and MTLCC based HESS which help to promote the commercialization of these technologies.

Course Outline

Time	Activities
8:30-8:45	Registration **(Executive Seminar Room S2.2-B2-53)**
8:45-10:00	Lectures delivered by Prof Hoay Beng **Gooi** Topic: Hierarchical Transactive Energy Management and Future Development Trend 1. System Overview and Intelligent Assessment Tool 2. MPC-based and PI-based Load Frequency Control 3. Some Aspects of Future Development Trend
10:00-10:30	Tea break **(Staff Lounge, S2.2-B4-06)**
10:30-11:45	Hardware and Software Demonstration: Microgrid System, MPC-based LFC, universal HIL Platform in the **Clean Energy Research Laboratory (S2-B7c-05)**.
11:45-12:45	Lunch **(Staff Lounge, S2.2-B4-06)**
12:45-14:00	Lectures delivered by Dr Eddy **Foo** and Dr Ujjal **Manandhar** Topic: Hardware in the Loop including CHIL and PHIL 1. Overview of Real Time Digital Simulator 2. Rapid Control Prototyping and Hardware in the loop concepts 3. CHIL and PHIL applications 4. Example on NTU microgrid HIL scenario
14:00-15:00	Lectures delivered by Prof Christopher **Lee** Topic: Power Electronics Converters in Hybrid Energy Storage System (HESS) 1. Introduction of Power Electronics Converters 2. Bidirectional Power Converter Topologies 3. Applications in HESS
15:00-15:30	Tea Break **(Executive Seminar Room S2.2-B2-53)**
15:30-16:30	Lectures delivered by Dr. Jian **Ye** and Dr. Benfei **Wang** Topic: Flexible Power Quality Conditioner (FPQC) and Multiport Three-level Cascaded Converter (MTLCC) interfaced HESS 1. Introduction to Power Quality 2. Design and control algorithms of FPQC 3. Configuration and control algorithms of MTLCC for HESS
16:30-17:45	Hardware and Software Demonstration: FPQC and MTLCC interfaced HESS in the **Clean Energy Research Laboratory (S2-B7c-05)**.

The details of the finalized course schedule will be available from the Short Course sub-menu at http://eeeweba.ntu.edu.sg/power_projects/ntu-HTEMS/default.asp a couple weeks before the scheduled course date.

Instructors

H. B. GOOI received his Ph.D. degree from Ohio State University in 1983. From 1983 to 1985 he was an Assistant Professor in the EE Department at Lafayette College. From 1985 to 1991 he was a Senior Engineer with Empros (now Siemens), USA where he was responsible for the design and testing of energy management system (EMS) projects. In 1991, he joined School of EEE, NTU as a Senior Lecturer and has been an Associate Professor since 1999. He is a registered professional engineer in USA and Singapore. He taught EMS courses for dispatchers at Power System Control Centre in Singapore, Indonesia and Malaysia. He was Deputy Head of Power Engineering Division during 2008-2014. He has served as an Editor of IEEE Transactions on Power Systems and IEEE Power Engineering Letters since 2016. He attracted more than S$10m research grants and serves as PI of EMA funded EIRP12 Project and US Navy funded ONRG Project. His current research interests include transactive energy management systems, energy storage, renewable energy sources, electricity market and spinning reserve.

Y. S. Foo, Eddy received his B.Eng. degree in Electrical and Electronic Engineering from Nanyang Technological University, Singapore, in 2009. Subsequently, he received his Ph.D. degree in Electrical and Electronic Engineering from Nanyang Technological University, Singapore, in 2016. Between 2014 and 2016, he worked as a research engineer under the Cambridge Centre for Advanced Research in Education in Singapore (CARES) project which is part of the CREATE program. Between 2012 and 2014, he served as a Teaching Assistant for NTU EEE and REP. He was awarded the NTU EEE outstanding teaching award in 2013. At present, he is a lecturer in the School of Electrical and Electronic Engineering at Nanyang Technological University, Singapore. His research interests are multi-agent systems, microgrid energy management systems, electricity markets, power hardware in the loop and renewable energy resources.

Christopher H. T. Lee received his B.Eng. in Electrical Engineering with 1st Class Honors at The University of Hong Kong (HKU) in 2009. He then served as an Instructor in a local school for two years. He obtained his Ph.D. in his alma mater with the Best Thesis Award in 2016. Subsequently, he has been awarded a Croucher Fellowship to further his research interests as a Postdoc Fellow at Massachusetts Institute of Technology (MIT). He has joined Nanyang Technological University as an Assistant Professor in October 2018.

Dr. Lee is an expert in electric motors and drives, renewable energies and electromechanical propulsion systems. He is currently a Visiting Assistant Professor at MIT and Honorary Assistant Professor at HKU. He is an IEEE Senior Member and a member of Editorial Board for IEEE Access and IET Renewable Power Generation.

Demonstrators

Dr. Benfei Wang received the B.Sc. degree in Electronic Information Science and Technology from University of Science and Technology of China, China, in 2011. He received the Ph.D. degree from Nanyang Technological University, Singapore, in 2017. He is currently a Research Fellow at the Energy Research Institute at NTU. His research interests include model predictive control, multi-port power converter, hybrid energy storage system and microgrids.

Dr. Jian Ye received the B.Eng. degree in electrical engineering and automation from Wuhan University, Wuhan, China, in 2012, and the M.Sc. and Ph.D. degrees in power engineering from the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, in 2013 and 2018, respectively. He is currently a Research Fellow at the Energy Research Institute at NTU. His research interests include power electronics for various applications such as connecting renewable energy sources, energy devices to microgrids, and power quality compensation.

Dr. Ujjal Manadhar received the B.E. degree in Electrical and Electronics Engineering from Kathmandu University, Nepal in 2013. He received his Ph.D. degree from Nanyang Technological University, Singapore in 2019. He is currently working as a postgraduate research assistant at the Energy Research Institute at NTU. His main study includes control strategies in DC and AC grid system with hybrid energy storage system. His research interest includes control strategies in DC grid, hybrid energy storage system, power hardware in loop simulation and power electronics control.

Who Should Attend?

This course is useful to engineers and managers working in clean energy, renewable energy, converter design and operation of smart grids, microgrids and intelligent energy systems. It is beneficial to anyone who wishes to know more about their development in Singapore. The course will be structured towards experience sharing and knowledge transfer.

Course Information	
Date:	April 29, 2019 (Monday)
Time:	8:30 to 18:00
Lecture Venue:	Executive Seminar Room (S2.2-B2-53), Block S2.2, Level B2, Room 53, School of Electrical & Electronic Engineering (EEE), NTU
Demo Venue:	Clean Energy Research Laboratory (S2-B7c-05), School of EEE, NTU
CPD Programme:	This course is qualified for 5 PDUs by Professional Engineers Board (PEB), Singapore. Please visit https://www.peb.gov.sg/course_calendar.aspx
Fee (net amount):	S$600 or on site S$700 (subject to space availability) Early Bird Registration: S$550 by 8 April 2019 Group Registration (3 or more from the same organization registered at the same time): S$500 by 15 April 2019 IEEE/IES Member: S$500 by 15 April 2019
Registration:	Please register at this link: https://goo.gl/forms/CQaMbX46xKfWGHpw2

Fees include refreshments, lunch and course notes. Payment is to be made payable to **IEEE Singapore Section** via a Singapore cheque or bank draft in Singapore dollars. Overseas participants may contact Mrs Jasmine Leong for details of TT transfer at:

IEEE Singapore Section Secretariat
Blk 121 Paya Lebar Way
#03-2801
Singapore 381121
Tel: (65) 6743 2523
Email: sec.singapore@ieee.org

Accommodation is available at Nanyang Executive Center on a first-come, first-served basis. Details are available at http://www.ntu.edu.sg/nec/Pages/default.aspx

The proposed course contents may be modified where practical and the course is subjected to a minimum participation before commencement.