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Design and Analysis of Three Phase Inverter with Two Buck/Boost MPPTs for DC Distribution System

Neeraj Kumar[1], G. Indirarani[2]
M. Tech ScholarDepartment of EEEVignanaBharathi Institute of Technology, Hyderabad
M. TechAssistant ProfessorDepartment of EEEVignanaBharathi Institute of Technology, Hyderabad

ABSTRACT
Anintegration and operation of a three-phase inverter with twobuck/boost maximum power point trackers (MPPTs) for dc-distribution applications. In a dc-distribution system, a three phase inverter isrequired to control the power flow between dc busand three phase ac grid, and to regulate the dc bus to a certainrange of voltages. A droop regulation mechanism according to the inverter inductor current levels to reduce capacitor size, balance power flow, and accommodate load variation is proposed. Since thephotovoltaic (PV) array voltage can vary from 0 to 5000 V, especially with thin-film PV panels, the MPPT topology is formed with buck and boost converters to operate at the dc-bus voltage around 4000 V, reducing the voltage stress of its followed inverter.
Additionally, the controller can online check the input configuration of the two MPPTs, equally distribute the PV-array output current to the two MPPTs in parallel operation, and switch control laws to smooth out mode transition. A comparison between the conventional boost MPPT and the proposed buck/boost MPPT integrated with a PV inverter is also presented. Asingle-phase bidirectional inverter with two buck/boost maximum power point trackers (MPPTs) by using the closed loop circuit. This project is workout bySimulink using mat lab.
Index Terms: Three Phase inverter, buck/boost maximum power point trackers (MPPTs), dc-distribution applications

I. INTRODUCTION

Many types of renewable energy, such as photovoltaic (PV), wind, tidal, and geothermal energy, have attracted a lot of attention over the past decade [1]–[3]. Among these natural resources, the PV energy is a main and appropriate renewable energy for low-voltage dc-distribution systems, owing to the merits of clean, quiet, pollution free, asnd abundant. In the dc-distribution applications, a power system, including re-newable distributed generators (DGs), dc loads (lighting, air conditioner, and electric vehicle), and a bidirectional inverter, is shown in Fig. 1, in which two PV arrays with two maximum power point trackers (MPPTs) are implemented. However, the *i–v* characteristics of the PV arrays are nonlinear, and they require MPPTs to draw the maximum power from each PV array. Moreover, the bidirectional inverter has to fulfill grid connection (sell power) and rectification (buy power) with power-factor correction (PFC) to control the power flow between dc bus and ac grid, and to regulate the dc bus to a certain range of voltages, suchas380± 10 V.

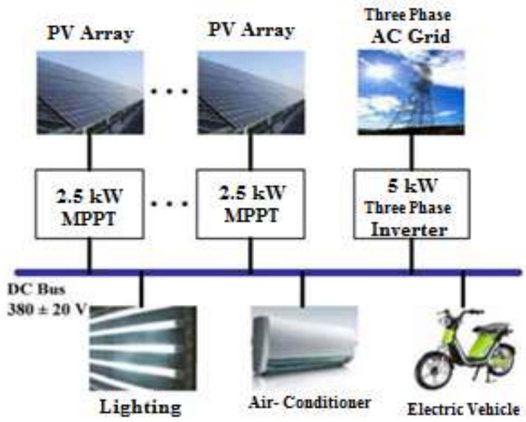

Fig. 1.Configuration of a dc-distribution system.

Nowadays, a conventional two-stage configuration is usually adopted in the PV inverter systems [4]–[8]. Each MPPT is realized with a boost converter to step up the PV-array voltage close to the specified dc-link voltage, as shown in Fig. 2. The boost converter is operated in by-pass mode when the PV-array voltage is higher than the dc-link voltage, and the inverter will function as an MPPT. However, since the characteristics of PV arrays are different from each other, the inverter operated in by-pass mode cannot track each individual maximum power point accurately, and the inverter suffers from as high-voltage stress as the open voltage of the arrays. To release this limitation, an MPPT topology, which combines buck and boost converters is proposed in

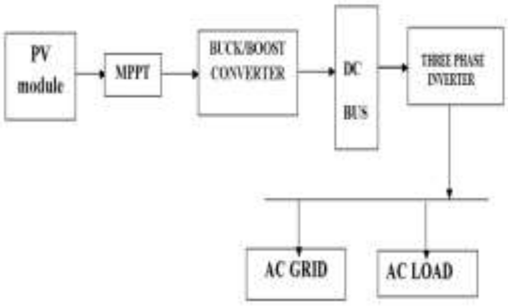

Fig.2. Block Diagram

this study, in which the control algorithm for tracking maximum power points is based on a perturbation and observation method. The MPPT will switch operation modes between buck and boost when the output voltage of a PV array is close to the dc-bus voltage. The designed controller can switch control laws to achieve smooth mode transition and fulfill online configuration check for the MPPTs, which can be either separate or in parallel connection, to draw the maximum power from the PV arrays more effectively. Additionally, a uniform current control scheme is introduced to the controller to equally distribute the PV-array output current to the two MPPTs in parallel operation.

The goals of this research are:

- To simulate and analyze the typical power in PV array.
- Basic overview of MPPTs to include tracking algorithms.
- Perturbation and observation tracking method.
- To simulate and analyze the methodology chosen for MPPTs.
- Building the case for the usage of multiple MPPTs.
- To determine the best control mode for proposed buck/boost.
- To implement a single-phase bidirectional inverter using AC and DC power supply unit.

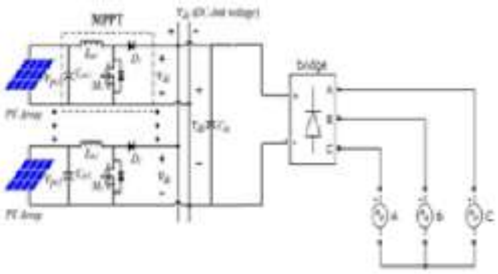

Fig.3. Conventional two-stage PV inverter system with boost-type MPPTs

II. THREE PHASE INVERTER FOR PHOTOVOLTAIC APPLICATION

To eliminate leakage ground current circulating through PV arrays and ground, several transformerlessinverter topologies were proposed [9]–[11]. Even though they can achieve high efficiency, they require more components than the conventional full-bridge topology. Thus, in this study, the bidirectional full-bridge inverter is operated with bipolar modulation to avoid leakage ground current and to save power components while still sustaining comparatively high efficiency to those in [9]–[11]. Note that a full-bridge inverter operated with bipolar modulation can achieve only low frequency common-mode voltage (vCM = ($v$dc− v_s)/2), resulting in low leakage ground current [9].

To regulate the dc-bus voltage for the grid-connected inverter, the controls, such as robust, adaptive, and fuzzy [12]–[14], were adopted. When adopting these controls for the studied dc-distribution system, a heavy step-load change at the dc-bus side will cause high dc-bus voltage variation and fluctuation, and the system might run abnormally or drop into under or over voltage protection. Bulky dc-bus capacitors can be adopted to increase the hold-up time and suppress the fluctuation of the dc-bus voltage [15], but it will increase the size and cost of the system significantly. Additionally, even though there are approaches to achieving fast dc-bus voltage dynamics, the systems with load connected to the dc bus have not been studied yet [16], [17]. Therefore, to operate the dc-distribution system efficiently while reducing the size of dc-bus capacitors, a droop regulation mechanism according to the inverter current levels is proposed in this study.

In this paper, operational principle and control laws of the system are first described, and the MPPT control algorithm, online configuration check, uniform current control, buck/boost mode transition, and dc-bus-voltage regulation mechanism are then addressed. Simulation results from a 5-kW, three-phase inverter with two buck/boost MPPTs are presented to verify the analysis and discussion.

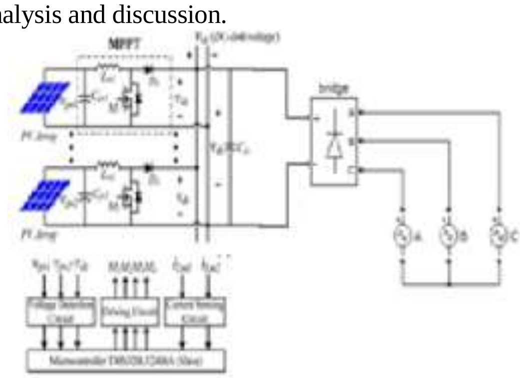

Fig. 3. Configuration of the studied PV inverter system with the buck/boost MPPTs

III. OPERATION AND ANALYSIS OF THE PROPOSED BUCK/BOOST MPPTs

The MPPT topology is formed from a buck converter and a boost converter but with a shared inductor to accommodate wide PV-array voltages from 0 to 600 V. For various PV-array applications, the two MPPTs will be connected separately or in parallel. The MPPT senses PV voltage *v*PV, dc-bus voltage *v*dc, and inductor current *iLm*into the single-chip microcontroller (TMS320LF2406 A) to determine operational mode and duty ratio for tracking the maximum power point accurately. When voltage *v*PV is higher than *v*dc, the MPPT is operated in buck mode, and switch *M*1 is turned ON to magnetize inductor $L_m$and thus increase inductor current *iLm*. While switch *M*1 is turned OFF, inductor L_m releases its stored energy through diodes *D*1 and *D*2. On the other hand, the MPPT is operated in boost mode when voltage *v*PV is lower than *v*dc, and switches *M*1 and *M*2 are turned ON to magnetize inductor L_m. While switch *M*2 is turned OFF, inductor L_m releases its stored energy through diode *D*2. Thus, the control laws can be expressed as follows

$$d_{buck} = \frac{V_{dc}}{V_{pv}}$$

And

$$d_{boost} = \frac{V_{dc} - Vpv}{V_{pv}}$$

To draw maximum power from PV arrays, a perturbation and observation control algorithm for tracking maximum power points is adopted. If the maximum power level of a PV array is higher than the power rating of an MPPT, the two MPPTs will be in parallel operation to function as a single MPPT. Thus, it requires an online configuration check to determine the connection types of the two MPPTs, separately or in parallel. Moreover, if the two MPPTs are in parallel operation, a uniform current control scheme is introduced to equally distribute the PV-array output current to the two MPPTs. The operational-mode transition control between buck and boost is also presented.

A. Perturbation and Observation Tracking Method

In this study, the MPPT controller tracks the maximum output power of a PV array based on the perturbation and observation tracking method. At the beginning, the controller will determine the operation mode of the proposed MPPT. When the MPPT is operated in boost mode, inductor current *iLm*is equal to output current *i*PV of the PV array; thus, the output power of the PV array can be expressed as follows:

*P*PV boost(*n*) = *v*PV(*n*) × *iLm*(*n*). (9)

On the other hand, when the proposed MPPT is operated in buck mode, inductor current *iLm*is equal to output current i_o; thus, the output power of the PV array can be expressed as follows:

*P*PV buck(*n*) = vd$_c$(*n*) × *iLm*(*n*). 10)

With this control algorithm, the controller tracks the peak power by increasing or decreasing the duty ratio periodically.

In this studied PV inverter system, there is a shared auxiliary power supply for the MPPTs and the inverter. Because the switching frequencies of the MPPT (25 kHz) and the inverter (20 kHz) are different, their switching noises might affect the accuracy of voltage and current sampling, especially under high-power condition. To avoid noise interference, the MPPTs are synchronized with the inverter, and the controller will update the duty ratio of the MPPT power stage every ten line cycles at the zero crossing of the line voltage. Additionally, since the single-phase PV inverter system has a twice line-frequency ripple voltage on the dc bus, this synchronization approach can also eliminate the ripple voltage effect and determine accurate output power of the PV arrays. When the output power of the PV arrays can be determined accurately, the proposed controller can track the maximum power point precisely.

B. Online MPPT Configuration Check

In order to track the maximum power point correctly and effectively, a scheme of online MPPT configuration check is proposed. A flowchart of the check algorithm is shown in Fig. 4. First, the MPPT determines if there is any PV array plugged in or removed from the system by checking voltage *v*PV for

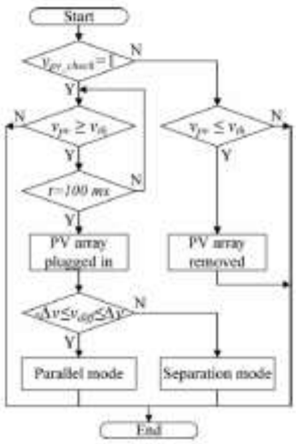

Fig. 4 Flowchart of online MPPT

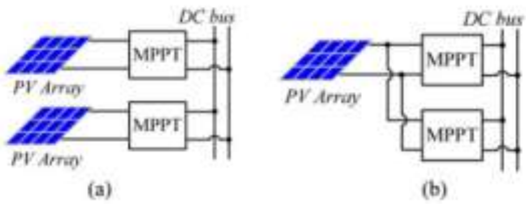

Fig. 5. Input configuration of the two MPPTs: (a) separately and (b) in parallel.

100 ms.If voltage *v*PV is higher than the threshold voltage *v*th, the controller determines that a new PV array is plugged into an MPPT. On the contrary, if voltage *v*PV is lower than *v*th, it means that a PV array is removed from an MPPT or there is no PV array. Next, if the input voltages of both

MPPTs are very close (within Δ*v*), the MPPT configuration will be determined as a parallel mode. On the contrary, the two MPPTs will be operated in separate mode. Moreover, a parallel verification algorithm is utilized to confirm the MPPT configuration check. The controller will perturb the duty ratio of one MPPT to examine if both MPPT input voltages are still identical to indentify the connection modes.

The system controller checks the configuration of the MPPTs every switching cycle. If the PV arrays are connected to the MPPTs separately, as shown in Fig. 5(a), the MPPTs will calculate their PV output power and tune their duty ratios individually. If the maximum power level of a PV array is higher than that of an MPPT, the two MPPTs will be connected to this PV array and operated synchronously, as shown in Fig. 5(b). When tracking the maximum PV output power, the MPPTs will sum up their input currents and equally distribute the total current to the two MPPTs based on a uniform current control scheme.

C. Uniform Current Control Scheme

There might exist differences between the two MPPTs, such as components, feedback signals, and noise levels, which will

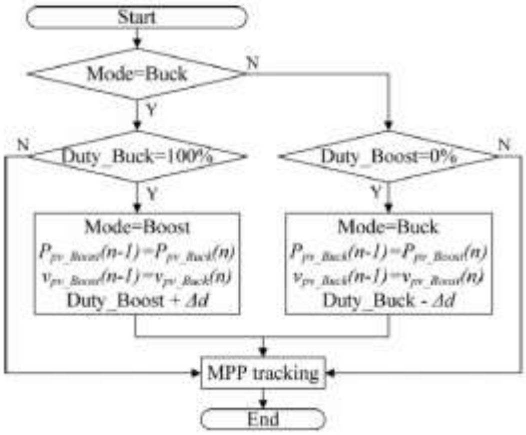

Fig. 6.Flowchart of the buck/boost mode transition algorithm.

result in current imbalance while they are connected in parallel. When a current imbalance occurs, the components with higher current level will suffer from higher temperature and shorter lifetime. Considering the component reliability and thermal problem, a uniform current control scheme is proposed and described as follows. First, we calculate the current difference (Δ*i*diff) between the two MPPTs to determine if a uniform current control is necessary. If the current difference Δ*i*diff is higher than a threshold value, the controller will vary the duty ratios (Δ*d*) of the MPPTs to achieve equal current distribution. The duty ratios of the two MPPTs are determined as follows:

$D_{PV1} \leftarrow D_{PV1} \pm \Delta d$

and

$D_{PV2} \leftarrow D_{PV2} \pm \Delta d$

in which when D_{PV1} is increased by Δ*d*andD_{PV2} will be decreased by Δ*d*and vice versa.

D. Buck–Boost Mode Transition

Since the operation range of the dc-bus voltage is limited within 380 ± 20 V (including ripple voltage) in the dc-distribution system, operational-mode transition between the buck and boost modes will be a critical control issue to accommodate a wide PV input voltage variation (0–600 V). When the proposed MPPT is operated in boost mode and voltage *v*PV is close to *v*dc, switch *M*2 is turned OFF and the duty ratio of switch *M*1 starts to decrease (–Δ*d*) from 100%. With this control scheme, current *i*PV of the PV array will charge input capacitor *Crv*, and voltage *v*PV can be raised up to a higher level to prevent mode fluctuation problems. On the contrary, switch *M*1 is continuously turned ON and the duty ratio of switch *M*2 starts to increase (+Δ*d*) from 0%, when *v*PV drops toward *v*dc during buck mode. Therefore, the MPPT can achieve smooth mode transition by tuning the duty ratios of the active switches. A flowchart of the buck/boost mode transition scheme is shown in Fig. 6.

IV. DC-BUS-VOLTAGE REGULATION MECHANISM

The proposed regulation mechanism is similar to the concept of the adaptive voltage position (AVP) method [20], but it is more like a droop one. In the discussed dc-distribution system, for reducing dc-bus capacitance and mode-change frequency, a droop dc-bus-voltage regulation mechanism is proposed, , in which the dc-bus voltage is regulated according to the inductor current linearly. When the bidirectional inverter sells higher power, which means less load-power requirement, the dc-bus voltage will be regulated to a higher level. If there is a heavy step-load change suddenly, this mechanism can avoid a voltage drop below 380 V abruptly and it will not change the operation mode from grid connection to rectification, or can avoid under voltage protection. On the other hand, when the bidirectional inverter buys higher power, the dc-bus voltage is regulated to a lower level, reducing the frequency of mode change, and thus, reducing the dc-bus capacitance around 15%.

When there exists a power imbalance between sourcing and loading at time *tx*1, for instance, the dc-bus voltage increases from *v*dc(*n* – 1) to v_c(*n*). We can determine the current difference Δ*i*dc between the source and the load from the voltage variation, and it can be expressed as follows:

$$\Delta i_{dc} = C_{dc}\frac{V_{dc}(n)-V_{dc}(n-1)}{t_n - t_{x1}}$$

From the linear dc-bus voltage regulation relationship, as shown in Fig. 8, the new steady-state voltage *v*dc can be obtained. Therefore, the adjustment current command *IA* can be determined. The control laws can adjust inductor-current command and regulate the dc-bus voltage to its corresponding level simultaneously. Since time *tx*1 is unpredictable, we approximate the time difference ($\Delta t = t_n - tx1$) with one line cycle *Tl*, and new inductor-current command *IA*(*n*) can be determined based on previous current command *IA*(*n* – 1) as follows:

$$I_A(n) = I_A(n-1) + f_1 C_{dc}\left(V_{dc}(n) - V_{dc}(n-1)\right) + f_1 C_{dc}\left(V_{dc}(n) - V_{dc}(n+1)\right)$$

where*fl*is the line frequency and

$$V_{dc}(n+1) = 380V + \frac{10}{23A} I_A(n+1) \frac{V_{dc}(n) + V_{dc}(n+1)}{220 * 2}$$

where

$$IA(n+1) = IA(n-1) + \Delta I \quad (16)$$

and

$$\Delta I = C_{dc}\frac{V_{dc}(n) - V_{dc}(n-1)}{T_l} = f_1 C_{dc}\left(V_{dc}(n) - V_{dc}(n-1)\right)$$

In (14), current *IA*(*n* – 1) is the current command given at *tn*−1 and *IA*(*n*) is the adjustment current command given at t_n. The inverter applies current command *IA*(*n*) to the controller for compensating the power imbalance on dc-bus, and dc-bus voltage $vd_c(n)$ will be regulated to voltage *v*dc(*n* + 1) at next line cycle *tn*+1, achieving power balance. In the afore-mentioned equations, current *IA*(*i*) denotes the average value of its full-wave rectified sinusoidal current waveforms. Due to the approximated time interval (*tn*–*tx*1) with one line cycle *Tl*, the inverter has to adjust the inductor current command *IA* once to tune voltage *v*dc on the load line, and the current command *IA* becomes the steady-state inductor current, i.e., *IA*(*i*)<—*IA*(*i*–1). However, if at *tn*+1, dc-bus voltage $vd_c(n+1)$ is not close to its corresponding voltage level enough (due to new power imbalance between t_n and *tn*+1), current *IA*(*n*) is treated as a new *IA*(*n* – 1), time t_n is *tn*−1, and a new *IA*(*n*) can be determined at *tn*+1 based on (14), achieving one-line-cycle regulation mechanism. The controller adjusts current command *IA* continuously until *v*dc comes back to the load line and balances the power on the dc bus. With one-line-cycle regulation mechanism, current distortion can be minimized. However, if there is an abrupt load change, the controller will update current command immediately to avoid under- or overvoltage.

V. SIMULATION

The circuit consists of two solar panels and two buck-boost choppers and two MPPT controllers to operate choppers, one dc buc capacitor and one three phase diode bridge rectifier

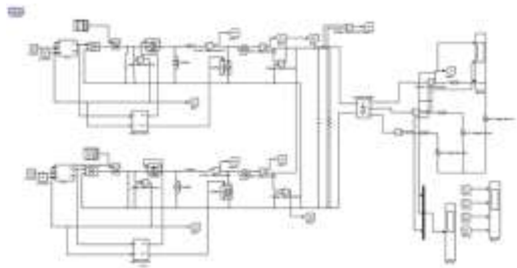

Fig.7 simulation circuit

At the beginning, the MPPTs track the maximum power point gradually due to a soft start and the inverter tunes current command *IA*(*n*) to regulate the dc-bus voltage, as shown in Fig. 8

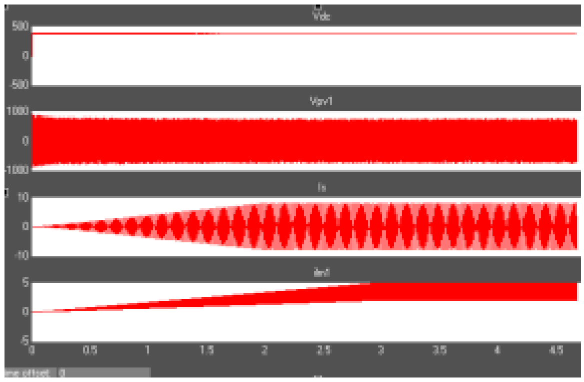

Fig. 8. Measured waveforms of PV output voltage *v*PV, dc-bus voltage *v*dc, and inductor currents *iLm*1 and *iLs*during MPPTs soft start.

When *v*PV1 and *v*PV2 are lower than the minimum start-up voltage (100 V) of the power supply, the controller determines that PV1 and PV2 arrays are removed from the MPPTs. Since the two capacitors were not fully discharged yet, there exist nonzero voltages.

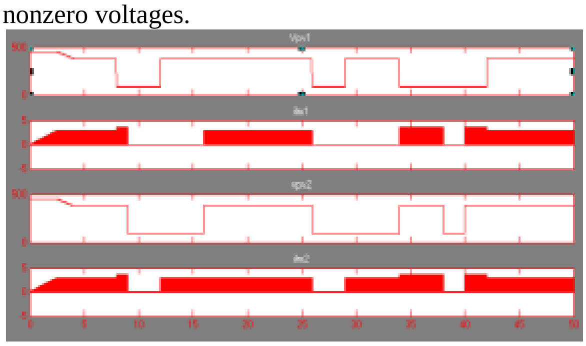

Fig.9 Measured waveforms of PV output voltage *v*PVand inductor current *iLm*during online MPPT configuration check: in parallel.


Fig.Measeured waveforms of three phase grid current

VI. CONCLUSION

In this paper, a three-phase inverter with two buck/boost MPPTs has been designed and implemented. The inverter controls the power flow between dc bus and ac grid, and regulates the dc bus to a certain range of voltages. A droop regulation mechanism according to the inductor current levels has been proposed to balance the power flow and accommodate load variation. Since the PV-array voltage can vary from 0 to 600 V, the MPPT topology is formed with buck and boost converters to operate at the dc-bus voltage around 380 V, reducing the voltage stress of its followed inverter..

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Author's Profile

Mr.Neeraj Kumar received B.Tech degree in Electrical and Electronics Engineering from ACE Engineering College, And currently pursuing M.Tech in Electrical and Electronics Engineering with PE&EDspecialization fromVignanaBharathiInstitute ofTechnology,aushapur, ghatkesar, rangareddydist, Telangana.His research interests include PowerQuality, Power Electronics and Electrical Drives,FACTS and Control Systems.

Mrs.G.Indira Rani presently working as Assistant professor in VBIT Engineering College, Aushapur, Ghatkesar, Rangareddy, Telangana, India.She received the B. Techdegree in Electrical & Electronics Engineering from BVCEC, JNTU Hyderabad.And then completed her M.Tech in Electrical & Electronics Engineering with PE&ED specialization at GNITS, JNTU Hyderabad. She has a teaching experience of 10 years.Her areas of interest are Power System, Power Electronics and Electrical Drives, FACTS, Switchgear and Protection.