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ETPL PELE - 001	Predictive dead time controller for GaN-based boost converters

A dynamic dead time controller is presented, specifically intended to operate in synchronous boost converters based on GaN field-effect transistor switches. These transistors have a reduced stored charge with respect to silicon metal-oxide-semiconductor field-effect transistors with similar breakdown voltage and series resistance, and can operate at higher frequencies with reduced switching losses. On the other hand, the voltage drop in reverse conduction is typically more than doubled with respect to silicon devices resulting in relevant power losses during the free-wheeling phases. Therefore, dynamic control of dead time can be profitably applied even in converters operating in the tens of volts range. The device presented in this study controls the switching delays taking into account both variations of the fall/rise times and of the turn-off/on delays, in order to keep dead time within a range of a few nanoseconds above its minimum value. A discrete-component prototype was designed, built in a synchronous boost converter and extensively tested at 1-2 MHz switching frequency, in a range of operating parameters corresponding to significant variations of the switching times (currents in the 1-6 A range, output voltage up to 50 V). The prototype demonstrated the capability to match dead time to actual operating conditions with a smooth and fast transient response.

ETPL PELE - 002	Modeling and Experimental Validation of a Bidirectional DC/DC Buck Power Electronic Converter-DC Motor System

This paper presents the modeling and experimental validation of a new topology for the DC/DC Buck power converter-DC motor system. The main objective of this topology is to achieve a bidirectional rotation on the DC motor shaft by using a DC/DC power converter. As a result of applying Kirchhoff's current and voltage laws the system mathematical model is obtained. Also, an analysis in steady-state of the system is presented. While, the reference trajectory generation associated to the states and controls of the system (expressed in terms of the voltage converter and motor angular velocity) is performed via differential flatness, which allows a trajectory tracking control in open-loop. The experimental validation of the herein presented model is carried out by means of Matlab-Simulink, ControlDesk, and a DS1104 from dSPACE. The experimental results confirm the validity of the mathematical model, for the general case, i.e., the time-varying trajectory tracking and not only the constant trajectories case.

ETPL PELE - 003	A Performance Investigation of a Four-Switch Three-Phase Inverter-Fed IM Drives at Low Speeds Using Fuzzy Logic and PI Controllers

This paper presents a speed controller using a fuzzy-logic controller (FLC) for indirect field-oriented control (IFOC) of induction motor (IM) drives fed by a four-switch three-phase (FSTP) inverter. In the proposed approach, the IM drive system is fed by an FSTP inverter instead of the traditional six-switch three-phase (SSTP) inverter for cost-effective low-power applications. The proposed FLC improves dynamic responses, and it is also designed with reduced computation burden. The complete IFOC scheme incorporating the FLC for IM drives fed by the proposed FSTP inverter is built in MATLAB/Simulink, and it is also experimentally implemented in real time using a DSP-DS1103 control board for a prototype 1.1-kW IM. The dynamic performance, robustness, and insensitivity of the proposed FLC with the FSTP inverter-fed IM drive is examined and compared to a traditional proportional-integral (PI) controller under speed tracking, load disturbances, and parameters variation, particularly at low speeds. It is found that the proposed FLC is more robust than the PI controller under load disturbances, and parameters variation. Moreover, the proposed FSTP IM drive is comparable with a traditional SSTP IM drive, considering its good dynamic performance, cost reduction, and low total harmonic distortion (THD).

ETPL PELE - 004	Sliding Mode Control of Single-Phase Grid-Connected Quasi-Z-Source Inverter.

Quasi-Z-source inverters (qZSIs) are nowadays increasingly used owing to advantages such as single-stage operation, lower component rating, and continuous input current and common dc rail. These benefits lead to investigate this converter for grid-connected applications. This paper presents a grid-connected qZSI with both ac and dc side control. Sliding mode control (SMC)-based controller for capacitor voltage regulation has been proposed to ensure a fast and dynamic response for wide variations in input voltage, output load, and reference controlled quantity. A detailed mathematical model of the system is presented. A stable and fast response of SMC has been demonstrated using simulation and is validated by experimental results.

ETPL PELE - 005	A 2-kW Single-Phase Seven-Level Flying Capacitor Multilevel Inverter with an Active Energy Buffer

High-efficiency and compact single-phase inverters are desirable in many applications such as solar energy harvesting and electric vehicle chargers. This paper presents a 2-kW, 60-Hz, 450-V DC-to-240-V AC power inverter, designed and tested subject to the specifications of the Google/IEEE Little Box Challenge. The inverter features a seven-level flying capacitor multilevel converter, with low-voltage GaN switches operating at 120 kHz. The inverter also includes an active buffer for twice-line-frequency power pulsation decoupling, which reduces the required capacitance by a factor of 8 compared to conventional passive decoupling capacitors, while maintaining an efficiency above 99%. The inverter prototype is a self-contained box that achieves a high power density of 216 W/in 3 and a peak overall efficiency of 97.6%, while meeting the constraints including input current ripple, load transient, thermal, and FCC Class B EMC specifications.

ETPL PELE - 006	Constrained decoupled power predictive controller for a single-phase grid-tied inverter.

This study presents a decoupled active and reactive power control technique, for a single-phase grid-tied inverter, using model predictive control (MPC). The proposed technique does not use conventional phase-locked loop, pulse-width modulation nor a synchronisation transform, which makes the control algorithm well suited for an all-digital implementation. The proposed controller minimises the number of switching state transitions required to control the grid-side current while simultaneously constraining the harmonics distortions and protecting the inverter from overcurrent condition. In this study, the switching frequency is reduced by using a look-up table to minimise the number of switching state transitions, which helps lowering down the switching losses. The proposed technique uses an adaptive weight factor which gives more priority to commanded power tracking during transient, and minimises the tracking error and switching frequency in steady state while constraining the harmonics distortion. This method improves the tracking performance as well as reduces the switching losses by minimising the switching frequency compared to the MPC with fixed weight factor and conventional decoupled power control. Thus, the outcome of proposed controller is a constraint multi-objective optimisation between the switching frequency reduction and grid-side current harmonics in terms of cost function with weighting factor.

ETPL PELE - 007	Three-phase battery storage system with transformer less cascaded multilevel inverter for distribution grid applications

A distributed generator (DG) based on renewable energy is a promising technology for the future of the electrical sector. DGs may benefit utility companies and customers in a variety of perspectives. However, DGs suffer from intermittent behaviour. Storage systems appear as an attractive solution to support the continuous operation of DGs. The technology within the storage also plays an important role, since DGs and storage are connected in medium-voltage grids. The use of batteries and the DC/AC converter in its conventional structure presents drawbacks in such grids. In this context, this study presents a three-phase transformerless battery storage system (BSS) based on a cascaded H-bridge inverter applied to a medium-voltage grid. The BSS is composed of eight equal series connected H-bridge converters, without bulk transformers, for connection to a distribution grid. Each converter contains 75, 12V/600Ah lead-acid batteries. The converters are controlled through pulse-width modulation at 600Hz. The BSS is able to keep working even with a failure of one of its converters. Reactive energy compensation not compensated by an existent passive filter is also performed. A case study with simulated and experimental results obtained through a hardware-in-the-loop system is presented showing the efficacy of the proposed BSS.

ETPL PELE - 008	Magnetic and Electrical Design Challenges of Inverter-Fed Permanent Magnet Synchronous Motors.

This paper provides new magnetic and electrical design guidelines for an integrated motor-drive system. Two significant design factors including the electric and magnetic loadings are targeted to address the issues associated with the combination of the motor and inverter performances. A set of new constraints is also introduced in terms of the magnetic, electrical and thermal limits of a field oriented controlled permanent magnet (PM) motor to highlight the corresponding design challenges. Moreover, the demagnetization proximity limit is incorporated to ensure a reliable and safe operation of the PM material. The results show that the magnetic and electrical requirements of an optimum integrated system are totally different from the optimum performances of either side of the system, i.e., the motor or the inverter. Finally, an efficiency/robustness trade-off is proposed and applied to the investigated motor-drive system to return a reliable and efficient design.

ETPL PELE - 009	DC-link capacitor voltage offset suppression with no filters for three-phase four-switch inverter fed PMSM drives.

The adjustable speed range for three-phase four-switch inverter (TPFSI) fed permanent magnet synchronous motor (PMSM) drives is seriously limited by the DC-link capacitor voltage offset in TPFSI. For the traditional offset suppression schemes, the low-pass filters or notch filters are necessary to extract the capacitor voltage offset, which will deteriorate the control performance of the offset suppression schemes severely, especially for the low-speed range. Thus, a novel offset suppression scheme with no filters is proposed to improve the situation. For the proposed scheme, to extract the offset with no filters, a new static coordinate is defined, the relationships between the fundamental/offset components of capacitor voltages and the load currents are revealed, based on which a simple algorithm is developed. Then, the desired compensatory current is obtained by a closed-loop control and injected into the stator current control loop. Experimental results have validated the proposed scheme.

ETPL PELE - 010	A Current Control Scheme of Brushless DC Motors Driven by Four-Switch Three-Phase Inverters.

Based on the brushless dc motor driven by a four-switch three-phase inverter (FSTPI), a current control scheme is proposed to reduce the current ripple of both the normal conduction region and the commutation region. Assuming c-phase winding is connected to the middle point of a dc-link capacitance, in the normal conduction region when a-phase and b-phase windings conduct, the current of c-phase may not be zero because of c-phase back electromotive force. The proposed strategy adds two regulating vectors into each control cycle based on the traditional PWM scheme, and controls the c-phase current to be zero by controlling the working time of the regulating vectors in each control cycle. In the commutation region, the noncommutated phase or the outgoing phase switch is modulated by comparing the change rate of the incoming and outgoing phase currents to maintain the noncommutated phase current constant. Compared with the traditional current control strategy, good control effect is kept in both the normal conduction region and the commutation region by accurately controlling the working time of the voltage vectors. The proposed strategy does not need to adjust the parameters of the controller, and it is simple and easy to implement. The experimental results prove the correctness and effectiveness of the control strategy.

ETPL PELE - 011	Single-Phase Inverter with Energy Buffer and DC–DC Conversion Circuits.

This paper proposes a new single-phase inverter topology and describes the control method for the proposed inverter. The inverter consists of an energy buffer circuit, a dc–dc conversion circuit and an H-bridge circuit. The energy buffer circuit and H-bridge circuit enable the proposed inverter to output a multilevel voltage according to the proposed pulse width modulation (PWM) technique. The dc–dc conversion circuit can charge the buffer capacitor continuously because the dc–dc conversion control cooperates with the PWM. Simulation results confirm that the proposed inverter can reduce the voltage harmonics in the output and the dc–dc conversion current in comparison to a conventional inverter consisting of a dc–dc conversion circuit and H-bridge circuit. Experiments demonstrate that the proposed inverter can output currents of low total harmonic distortion and have higher efficiency than the conventional inverter. In addition, it is confirmed that these features of the proposed inverter contribute to the suppression of the circuit volume in spite of the increase in the number of devices in the circuit.

ETPL PELE - 012	Bidirectional Single-Stage Grid-Connected Inverter for a Battery Energy Storage System.

The objective of this paper is to propose a bidirectional single-stage grid-connected inverter (BSG-inverter) for the battery energy storage system. The proposed BSG-inverter is composed of multiple bidirectional buck–boost type dc–dc converters (BBCs) and a dc–ac unfolder. Advantages of the proposed BSG-inverter include: single-stage power conversion, low battery and dc-bus voltages, pulsating charging/discharging currents, and individual power control for each battery module. Therefore, the equalization, lifetime extension, and capacity flexibility of the battery energy storage system can be achieved. Based on the developed equations, the power flow of the battery system can be controlled without the need of input current sensor. Also, with the interleaved operation between BBCs, the current ripple of the output inductor can be reduced too. The computer simulations and hardware experimental results are shown to verify the performance of the proposed BSG-inverter.

ETPL PELE - 013	Three-Phase Three-Level Flying Capacitors Split-Source Inverters: Analysis and Modulation.

Single-stage dc–ac power converters with boost capabilities offer an interesting alternative compared to two-stage architecture. One of the recently proposed single-stage dc–ac power converters is the split-source inverter (SSI). This paper extends the SSI topology from the two-level operation to the three-level one using the flying capacitors (FCs) configuration. Among the diode-clamped SSI (DC-SSI) and FC-SSI, the second one is proposed in order to avoid the need of two isolated dc sources. This paper shows that the FC-SSI provides additional merits compared to the two-level SSI in terms of input inductance requirements using the same switching frequency, voltage stresses across the active switches, and total harmonic distortion of the output voltage. Such results are obtained by discussing the analysis and the modulation of this topology, considering some simulation results, and comparing it to some other existing topologies to show its properties and limitations. Finally, a reduced-scale 1.5-kVA three-level FC-SSI is implemented experimentally to validate its functionality and verify the proposed analysis and modulation properties.

ETPL PELE - 014	Dynamic Voltage Restorer Using Switching Cell Structured Multilevel AC–AC Converter.

Dynamic voltage restorer (DVR) technology has become a mature power quality product. In high-power applications, DVR using a multilevel converter is commonly used. However, DVR using a multilevel direct pulse width modulation (PWM) ac–ac converter has not been well studied. This paper presents a new DVR topology using a cascaded multilevel direct PWM ac–ac converter. In the proposed scheme, the unit cell of the multilevel converter consists of a single-phase PWM ac-ac converter using switching cell structure with coupled inductors. Therefore, the multilevel converter can be short- and open-circuited without damaging the switching devices. Neither lossy RC snubber nor a dedicated soft commutation strategy is required in the proposed DVR. This improves the reliability of the DVR system. The output voltage levels of the multilevel converter increase with the number of cascaded unit cells, and a high ac output voltage is obtained by using low-voltage-rating switching devices. Furthermore, a phase-shifted PWM technique is applied to significantly reduce the size of the output filter inductor. A 1-kW prototype of single-phase DVR is developed, and its performance is experimentally verified. Finally, the simulation results are shown for a three-phase DVR system.

ETPL PELE - 015	Single Switch Non isolated Ultra-Step-Up DC–DC Converter with an Integrated Coupled Inductor for High Boost Applications.

This paper introduces a new single-switch nonisolated dc–dc converter with very high voltage gain and reduced semiconductor voltage stress. The converter utilizes an integrated autotransformer and a coupled inductor on the same core in order to achieve a very high voltage gain without using extreme duty cycle. Furthermore, a passive lossless clamp circuit recycles the leakage energy of the coupled magnetics and alleviates the voltage spikes across the main switch. This feature along with low stress on the switching device enables the designer to use a low voltage and low $R_{DS\text{-}on}$ MOSFET, which reduces cost, as well as conduction and turn on losses of the switch. The principle of operation, theoretical analysis, and comparison supported by some key simulation and experimental results of a 500 W prototype are presented.

ETPL PELE - 016	A Three-Phase Modular Multilevel DC–DC Converter for Power Electronic Transformer Applications.

A three-phase modular multilevel dc-dc converter is proposed and analyzed for power electronic transformer (PET) applications. Similar to a dual active bridge converter, the proposed converter comprises two three-phase inverters/rectifiers, coupled via a medium frequency (MF) transformer. The modular multilevel converter structure is used in the medium-voltage side to meet the high-voltage requirements and to reduce the dv/dt stress on the MF transformer. The frequency of the voltage through MF transformer (isolation frequency) is the same as the switching frequency of the power semiconductor devices, and zero-voltage switching-ON can be achieved for all the devices. With only one three-phase MF transformer, the proposed topology can greatly simplify the transformer design compared with the existed input-series output-parallel dc-dc converter structures for PET applications. A dual-phase-shift method is presented to control the output power and to balance the submodule capacitor voltages. Simulations and experimental results are provided to validate the theoretical analysis.

ETPL PELE - 017	A New Three-Phase AC–DC–AC Multilevel Converter Based on Cascaded Three-Leg Converters.

This paper proposes and investigates a new three-phase ac–dc–ac multilevel conversion system obtained from cascaded three-leg converters. Such configuration presents advantages in terms of reduced switch blocking voltages and consequently lower dc-link voltage rating. Operating principles, a pulse-width modulation (PWM) technique based on vector approach, and a control strategy are presented. The operation with different dc-link voltage values and a balancing method are discussed, and is supported by simulation and experimental results. The PWM technique is able to generate multilevel voltage waveforms, which permits reducing the switching frequency stress leading to reduced semiconductor losses. Simulation results are used to compare the proposed configuration with a conventional solution in terms of harmonic distortion and semiconductor losses. Experimental results demonstrate the feasibility of the studied converter, and were obtained by using a downscaled prototype with insulated gate bipolar transistors with dedicated drives and a digital signal processor with appropriated plug-in boards and sensors.

ETPL PELE - 018	Design and implementation of closed-loop control system for buck converter using different techniques.

Comparing between different techniques for the design and implementation of closed-loop control systems for buck converters is carried out. Controllers used for this comparison are integral, proportional plus integral (PI) controllers and artificial intelligence are represented in fuzzy logic controller (FLC) and tuned fuzzy logic controller (TFLC). Design and implementation of a control system demand the role of effective techniques that offer simple and pragmatic solutions in society to meet the performance requirements despite system disturbances and uncertainties. The occurrence of nonlinear phenomena in buck converters makes their analysis and control difficult. Classical linear techniques have stability limitations around the operating points. Hence digital and nonlinear stabilizing control methods must be applied to ensure large-signal stability. Fuzzy control has also been employed to control buck converters because of its simplicity, simplicity of design and simplicity of implementation. Fuzzy controllers are easily suited to nonlinear time-variant systems and do not require an accurate mathematical model for the system being controlled. They are usually designed based on expert knowledge of the converters. In this survey, the design procedures of integral, proportional plus integral, fuzzy logic, and tuned fuzzy logic controllers are presented.

ETPL PELE - 019	High-Performance Quasi-Z-Source Series Resonant DC–DC Converter for Photovoltaic Module-Level Power Electronics Applications

This paper presents the high-performance quasi-Z-source series resonant dc-dc converter as a candidate topology for the photovoltaic module-level power electronics applications. The converter features a wide input voltage and load regulation range thanks to the multimode operation, i.e., when the shoot-through pulse width modulation and phase-shift modulation are combined in a single switching stage to realize the boost and buck operating modes, respectively. Our experiments confirmed that the proposed converter is capable of ensuring ripple-free 400 V output voltage within the sixfold variation of the input voltage (from 10 to 60 V). The converter prototype assembled achieved a maximum efficiency of 97.4%, which includes the auxiliary power and control system losses.

ETPL PELE - 020	High-efficiency low-cost AC/AC buck converter with stability analysis

The commutation issue is the most important limiting factor of expanding AC chopper applications, which in most cases are solved by employing snubber circuits, implementing sensor-based selective switching patterns and utilising resonant circuits. To overcome the commutation problem, this study proposes a novel non-resonant AC/AC buck converter with no snubber circuits and no sensor-based switching patterns. The introduced hardware configuration and the proposed control strategy provide a path for an inductive load current in all switching states. This converter offers higher reliability and efficiency as well as lower cost compared to the AC choppers with snubber circuits or voltage and current sensors for performing a selective switching. This study presents the operation principles of the proposed hardware configuration and derives the stability condition thorough mathematical analyses. Moreover, the achievements are evaluated by simulation and verified by experiments.

ETPL PELE - 021	Reliability improvement of transistor clamped H-bridge-based cascaded multilevel inverter

Reduced voltage stress and low-total harmonic distortion are the main causes for such widespread application of multilevel inverters (MLIs) in various industrial sectors. However, reliability is one of the major concerns of MLIs as it uses a large number of switches as compared with two-level inverters. Therefore, a newly developed transistor clamped H-bridge inverter is proposed in the literature which uses a relatively less number of switches and DC sources as compared with cascaded H-bridge but lacks in reliability due to the absence of redundant states. Hence, in this study, the reliability improvement strategy for newly developed five-level transistor clamped H-bridge-based cascaded inverter is proposed which can be generalised for any number of levels. In the proposed fault tolerant strategy, the fault can be broadly classified based on the two main legs of the proposed inverter. Moreover, the proposed fault tolerant strategy does not require any kind of external circuit for maintaining its capacitor voltage in the balanced state. Finally, to validate the concept, a laboratory prototype of the five-level inverter is developed and results are obtained successfully.

ETPL PELE - 022	A Transformer less Bipolar Modular Multilevel DC–DC Converter with Wide Voltage Ratios

This paper presents a transformerless bipolar dc–dc converter based on series-connected submodules. It is intended for transforming dc voltage and managing power flow for medium/high-voltage dc grids. The dc–dc converter is composed of positive-pole and negative-pole subsystems, each of which consists of six arms/branches. Every two arms and one branch are constructed into a T-type circuit with the outer terminals interface to primary- and secondary-side dc buses. The two T-type circuits in one subsystem are connected in parallel to transmit power between primary and secondary sides. The transformerless structure (none bulky coupled inductors as well) solves the challengeable insulation and cooling issues of the extremely high-power magnetics in prior arts, while not sacrificing the power efficiency and system reliability. A ± 10-kV 2-MW simulation model performed in MATLAB/Simulink verifies the feasibility of the bipolar dc–dc converter. Experimental results obtained from a laboratory setup also confirm the validation of the proposal.

ETPL PELE - 023	A Highly Reliable and High-Efficiency Quasi Single-Stage Buck–Boost Inverter

To regulate an output ac voltage in inverter systems having wide input dc voltage variation, a buck-boost power conditioning system is preferred. This paper proposes a novel high-efficiency quasi single-stage single-phase buck-boost inverter. The proposed inverter can solve current shoot-through problem and eliminate PWM dead time, which leads to greatly enhanced system reliability. It allows bidirectional power flow and can use MOSFET as switching device without body diode conducting. The reverse recovery issues and related loss of the MOSFET body diode can be eliminated. The use of MOSFET contributes to the reduction of switching and conduction losses. Also, the proposed inverter can be operated with simple pulse width modulation (PWM) control and can be designed at higher switching frequency to reduce the volume of passive components. The detailed experimental results are provided to show the advantages of the proposed inverter. Efficiency measurement shows that using simple PWM control the proposed inverter can obtain peak efficiency of 97.8% for 1.1-kW output power at 30-kHz switching frequency.

ETPL PELE - 024	A Novel Step-Up Multi input DC–DC Converter for Hybrid Electric Vehicles Application

In this paper, a multiinput dc-dc converter is proposed and studied for hybrid electric vehicles. Compared to conventional works, the output gain is enhanced. Fuel cell (FC), photovoltaic panel, and energy storage system are the input sources for the proposed converter. The FC is considered as the main power supply, and roof-top PV is employed to charge the battery, increase the efficiency, and reduce fuel economy. The converter has the capability of providing the demanded power by load in absence of one or two resources. Moreover, the power management strategy is described and applied in a control method. A prototype of the converter is also implemented and tested to verify the analysis.

ETPL PELE - 025	Reliability Evaluation of Large Scale Battery Energy Storage Systems

This paper analyzes the reliability of large scale battery storage systems consisting of multiple battery modules. The whole system reliability assessment is based on the reliability evaluation of system components including individual battery modules and power electronic converters. In order to evaluate the reliability of a battery module, a reliability model based on the state of health of individual battery cells is introduced. The state of health of a battery cell is calculated based on the capacity fade of the cell using a weighted Ampere-hour throughput method. A universal generating function-based method is then introduced to evaluate the reliability of the battery module. The reliability model of dc/ac power electronic converters is also presented in this paper. The reliability analysis is conducted for battery storage systems with different system configurations and management strategies, and the influence of system configuration on the reliability of battery system is studied. Comparative studies are conducted for a classic battery energy storage system (BESS) and a reconfigurable BESS (RBESS) to demonstrate the advantages of having a reconfigurable system topology. The comparison results show that the proposed RBESS has higher system reliability and more power outputs than the classic BESS.

ETPL PELE - 026	Modified Synchronous Pulse width Modulation of Current-Fed Five-Level Inverter for Solar Integration

Large-scale photovoltaic (LSPV) energy conversion systems have been installed at many places across the world. The essential component of the LSPV system is the dc-ac conversion stage. The usage of multilevel converters is one of the recent advances in the dc-ac conversion stage of the LSPV system to enable transformer-less inversion. Current-fed multilevel inverter has been chosen in this paper as it provides high power inversion with inherent voltage boosting, and thus, avoids the usage of transformer. High power conversion necessitates low device switching frequency operation in order to satisfy thermal constraint of semiconductor devices and also to improve efficiency. However, low device switching frequency operation leads to higher harmonic distortion of inverter output currents. Synchronous optimal pulsewidth modulation (SOP) technique is an emerging low device switching frequency modulation technique that has been successfully implemented for voltage-source multilevel inverters. However, the state-of-the-art SOP technique cannot be directly applied to modulate current-source multilevel inverter topologies due to additional constraints on the switching commutations. Therefore, the purpose of our study was to propose a modified SOP technique to achieve: low device switching frequency and minimal harmonic distortion of inverter output currents. The topology of current-fed five-level inverter was used for demonstrating the performance of proposed technique. A generalized conversion method was introduced in the modified SOP technique for including switching constraints of the current-fed inverter. In addition, a state-sequencing machine was developed by utilizing redundant inverter states to produce equal switching commutation among all semiconductor devices at minimal switching frequency of 350 Hz. The experimental results obtained from the five-level current-source inverter of 1.2 kW demonstrated the effectiveness of the proposed SOP technique.

ETPL PELE - 027	A Three-Level LC-Switching-Based Voltage Boost NPC Inverter

A single-stage high-voltage gain boost inverter is getting popularity in applications like solar photovoltaic, fuel cell, uninterruptible power system (UPS) systems, etc. Recently, single-stage voltage boost multilevel Z-source inverter (ZSI) and quasi-Z-source inverter (QZSI) have been proposed for dc-ac power conversion with improved power quality. Multilevel ZSI uses more number of high-power passive components in the intermediate network, which increase the system size and weight. Also, its input current is discontinuous in nature which is not desirable in some of the applications like fuel cell, UPS systems, hybrid electric vehicle, etc. In this paper, a continuous current input three-level LC-switching-based voltage boost neutral-point-clamped inverter is proposed, which uses comparatively less number of high-power passive components at the same time retains all the advantages of multilevel QZSI/ZSI. It is able to boost the input dc voltage and give required three-level ac output voltage in a single stage. Steady-state analysis of the proposed inverter is discussed to formulate the relationship between the input dc voltage and three-level ac output voltage. A unipolar pulse width modulation technique devised for the proposed inverter to eliminate first center band harmonics is also presented. The proposed converter has been verified by simulation in MATLAB Simulink as well as performing experiment with the help of a laboratory prototype.

ETPL PELE - 028	A New Single-Phase Switched-Coupled-Inductor DC–AC Inverter for Photovoltaic Systems

This paper presents a new single-phase switched-coupled-inductor dc-ac inverter featuring higher voltage gain than the existing single-phase qZ-source and semi-Z-source inverters. Similar to the single-phase qZ-source and semi-Z-source inverters, the proposed inverter also has common grounds between the dc input and ac output voltages, which is beneficial especially for photovoltaic inverter systems. The inverter volume and maximum current flowing can be reduced significantly through the coupling of all inductors. A theoretical analysis of the proposed inverter is described and a 280-W experimental prototype is built to verify the performance of the inverter.

ETPL PELE - 029	Hybrid Z-Source Boost DC–DC Converters

This paper presents a new family of hybrid Z-source boost dc-dc converters intended for photovoltaic applications, where the high step-up dc-dc converters are demanded to boost the low-source voltages to a predefined grid voltage. Because the boost capabilities of the traditional Z-source networks are limited, the proposed converters are composed of combine traditional Z-source networks in different ways to enhance the boost abilities of the traditional Z-source networks. The new version of the proposed Z-source converters is termed as hybrid Z-source boost dc-dc converters to satisfy the traditional benefits of Z-source networks with stronger voltage boost abilities which can also be applied to dc-ac, ac-ac, and ac-dc power conversions. The performances of the proposed converters are compared with other Z-source networks behaviors. The simulation and experimental results of the proposed converters are validated at different operating conditions.

ETPL PELE - 030	Maximum Boost Control of Diode-Assisted Buck–Boost Voltage-Source Inverter with Minimum Switching Frequency

Diode-assisted buck-boost voltage-source inverter achieves high voltage gain by introducing a switch-capacitor based high step-up dc-dc circuit between the dc source and inverter bridge. As for the unique structure, various pulse width modulation (PWM) strategies are developed with regard to the chopped intermediate dc-link voltage. In order to maximize voltage gain and increase efficiency, this paper proposes a novel PWM strategy. It regulates the average value of intermediate dc-link voltage in one switching time period (T_s) the same as the instantaneous maximum value of three-phase line voltage by controlling the front boost circuit. Then, the equivalent switching frequency of power devices in the inverter bridge can be reduced to $1/3f_s$($f_s = 1/T_s$). The operating principle and closed-loop controller design are analyzed and verified by simulations and experiments. Compared with existing PWM strategies, the new control strategy demonstrates less power device requirement and higher efficiency in high voltage gain applications. It is a more competitive topology for wide range dc/ac voltage regulation in renewable energy applications. Furthermore, with new control strategy, the dc-side inductor current and capacitor voltage contains six-time line-frequency ripples. To overcome the undesired influence of low frequency ripples, it is also suitable for 400-800 Hz medium frequency aircraft and vessel power supply system.

ETPL PELE - 031	A Novel ZVS DC–DC Full-Bridge Converter with Hold-Up Time Operation

Two stage ac–dc converters consisting of front-end power factor correction ac–dc boost converter followed by an isolated dc–dc converter form the industry workhorses for powering network servers, telecom, and other dc loads. For safe and uninterrupted operation during sudden intermittences in power supplied from the ac mains, the ac–dc power converter should be able to supply the load with constant dc output voltage in order to prevent them from unwanted resetting or in other words exhibit sufficient hold-up time (HUT) operation. This paper proposes a novel dc–dc nonresonant full-bridge converter with extended HUT capability and reduced dc-link storage capacitance.

ETPL PELE - 032	Variable-Angle Phase-Shifted PWM for Multilevel Three-Cell Cascaded H-Bridge Converters

Multilevel cascaded H-bridge converters have become a mature technology for applications where high-power medium ac voltages are required. Normal operation of multilevel cascaded H-bridge converters assumes that all power cells have the same dc voltage, and each power cell generates the same voltage averaged over a sampling period using a conventional phase-shifted pulse width modulation (PWM) technique. However, this modulation method does not achieve good results under unbalanced operation per H-bridge in the power converter, which may happen in grid-connected applications such as photovoltaic or battery energy storage systems. In the paper, a simplified mathematical analysis of the phase-shifted PWM technique is presented. In addition, a modification of this conventional modulation method using variable shift angles between the power cells is introduced. This modification leads to the elimination of harmonic distortion of low-order harmonics due to the switching (triangular carrier frequency and its multiples) even under unbalanced operational conditions. The analysis is particularized for a three-cell cascaded H-bridge converter, and experimental results are presented to demonstrate the good performance of the proposed modulation method.

ETPL PELE - 033	A Modular Multilevel DC–DC Converter Topology with a Wide Range of Output Voltage

To solve some problems caused by the ac control method used for the existing modular multilevel dc-dc converter (MMDC), this paper has proposed a new MMDC topology with a wide range of output voltage by means of dc control. By reconstructing the submodule structure, the converter has a power branch and an auxiliary balance branch, which are used to transmit dc power and balance the capacitor voltage, respectively. Both dc analysis and control method are adopted to establish a mathematical model so as to deduce the mathematical relationships between the key electrical parameters. Moreover, what have been done include analyzing the self-balancing principle of the capacitor voltage and the mechanism of the auxiliary balance branch, calculating the related parameters of the capacitor voltage fluctuation, and presenting a dc closed-loop control strategy based on a small-signal model. The analyses of the steady and dynamic states in combination with simulation and experiment show that the proposed converter can stably operate in the mode of dc control, with a large adjustable range of output voltage, a small fluctuation in voltage of the capacitor, and the ability of the inductor to suppress the spike of the auxiliary balance current effectively so as to reduce the impact on the device.

ETPL PELE - 034	A Flying-Capacitor Modular Multilevel Converter for Medium-Voltage Motor Drive

This paper presents a flying-capacitor modular multilevel converter (FC-MMC) based on series-connected submodules. It is intended for completely improving the performance of a medium-voltage motor drive system in the entire speed range especially at zero/low speed under rated torque condition. The proposed FC-MMC circuit is characterized by the cross connection of upper and lower arm middle taps through a flying capacitor in per phase leg. By properly controlling the ac current flowing through the flying capacitor, the power balance between upper and lower arms is achieved, leading to very small voltage ripples on submodule dc capacitors in the entire speed range from standstill to rated speed even under the rated torque condition. Meanwhile, no common-mode voltage is injected. Simulation results obtained from a 4160-V 1-MW model show that the proposed FC-MMC along with the proposed control method performances satisfactorily in dynamic and static state even when operated at zero/low speed. Experiments on a downscaled prototype also prove the effectiveness of the proposal.

ETPL PELE - 035	Model-free predictive current control for three-phase AC/DC converters

A novel model-free predictive current control (MFPCC) approach for three-phase AC/DC converters is proposed, which only measures the input currents and calculates their differences under different switching states. Existing model-based predictive current control (MBPCC) methods are based on converter models and thus require the knowledge of input current, input and terminal voltages, resistance, and inductance. Compared to the MBPCC, the main advantages of the proposed MFPCC include eliminations of the converter model, multiplication operations, and tuning of system parameters. Simulation results show that the proposed MFPCC controls the input current slightly better than does the MBPCC. Experimental results are provided to validate the effectiveness of the proposed method, which are obtained from a three-phase AC/DC converter under the specifications of 380 V output voltage, 220 V/AC input voltage, and 1000 W output power. The measured harmonics orders 2-19 are shown to meet the IEC61000-3-2 Class A standard under 1000 W of output power. To the authors' best knowledge, it is the first MFPCC for such applications.

ETPL PELE - 036	A Single-Stage High-Frequency Resonant AC/AC Converter

In many applications, such as large-scale LCD panel backlighting, street lighting, tunnel lighting, etc., an ac/dc light-emitting diode (LED) driver should realize the following three functions at least: power factor correction, multichannel constant current outputs, and galvanic isolation. A novel two-stage multichannel constant current ac/dc LED driver with a low cost and simple structure is proposed in this paper, which is composed of a high-frequency resonant ac/ac converter and as many passive LCL-T resonant rectifiers as the number of the output channels. The high frequency resonant ac/ac converter is focused on in this paper, which converts the ac-line input voltage into high frequency sinusoidal output voltage. First, topology derivation of the single-stage high-frequency resonant ac/ac converter is presented, also the operating principle of it. Then, the steady-state performance of it is completely analyzed, including its input power factor, voltage gain, total harmonic distortion of its output voltage, and its soft-switching condition. Finally, a 130 W prototype is built and the experimental results are given to verify the theoretical analysis.

ETPL PELE - 037	Distributed Optimal Coordination for Distributed Energy Resources in Power Systems

Driven by smart grid technologies, distributed energy resources (DERs) have been rapidly developing in recent years for improving reliability and efficiency of distribution systems. Emerging DERs require effective and efficient coordination in order to reap their potential benefits. In this paper, we consider an optimal DER coordination problem over multiple time periods subject to constraints at both system and device levels. Fully distributed algorithms are proposed to dynamically and automatically coordinate distributed generators with multiple/single storages. With the proposed algorithms, the coordination agent at each DER maintains only a set of variables and updates them through information exchange with a few neighbors. We show that the proposed algorithms with properly chosen parameters solve the DER coordination problem as long as the underlying communication network is connected. The simulation results are used to illustrate and validate the proposed method.

ETPL PELE - 038	Multiple Solutions of Optimal PMU Placement Using Exponential Binary PSO Algorithm for Smart Grid Applications

For smart grid execution, one of the most important requirements is fast, precise, and efficient synchronized measurements, which are possible by phasor measurement unit (PMU). To achieve fully observable network with the least number of PMUs, optimal placement of PMU (OPP) is crucial. In trying to achieve OPP, priority may be given at critical buses, generator buses, or buses that are meant for future extension. Also, different applications will have to be kept in view while prioritizing PMU placement. Hence, OPP with multiple solutions (MSs) can offer better flexibility for different placement strategies as it can meet the best solution based on the requirements. To provide MSs, an effective exponential binary particle swarm optimization (EBPSO) algorithm is developed. In this algorithm, a nonlinear inertia-weight-coefficient is used to improve the searching capability. To incorporate previous position of particle, two innovative mathematical equations that can update particle's position are formulated. For quick and reliable convergence, two useful filtration techniques that can facilitate MSs are applied. Single mutation operator is conditionally applied to avoid stagnation. The EBPSO algorithm is so developed that it can provide MSs for various practical contingencies, such as single PMU outage and single line outage for different systems.

ETPL PELE - 039	Optimal PMU Placement for the System Observability Based on System Topology Model

In order to improve the synchronous phasor measurement unit (PMU) configuration efficiency and enlarge its application in the large-scale system, a novel PMU configuration method based on the system topology model and considering zero injection buses is proposed. This proposed method considers different cases of buses connection including leaf nodes, buses with the most and same number of connection branches and buses with two branches. For the buses with the most number of connection branches, the degree of links between buses is proposed to determine PMU placement. In addition, in the process of PMU configuration, the observable and unobservable buses are directly obtained by topology model, which avoids matrix operations and speeds up the speed. The proposed method is tested on the three systems and the results show the proposed method is correct and effective.

ETPL PELE - 040	A Flexible Voltage Bus Converter for the 48-/12-V Dual Supply System in Electrified Vehicles

Due to an increasing in-vehicle electric load demand, a new 48-V electric system architecture proposed by German premier car manufacturers has been gaining increasing attention recently for electrified vehicles. In this paper, a multiple-voltage bus converter for the 48-V and existing 12-V dual supply system, providing additional flexible dc bus voltages, is proposed. The proposed converter can provide a dual flexible dc voltage bus and an additional dependent voltage bus while simultaneously managing the 12-V supply net using only one single-leg switch pole and a diode. The additional dc voltage buses will provide more options to accommodate variable electric load components in a vehicle, improving their power density. Due to the multiple control objectives, the single-leg pole requires a multimode switching strategy to regulate the additional bus voltages. To improve the onboard vehicle system reliability and performance, an impedance network structure is implemented in the converter to obtain a dead-time-free pulsewidth modulation (PWM). Simulation and experimental results are presented to verify the feasibility and effectiveness of the proposed structure and control method.

ETPL PELE - 041	Experimental Validation of a Single DC Bus Cascaded H-Bridge Multilevel Inverter for Multistring Photovoltaic Systems

For large-scale photovoltaic (PV) systems, the multistring configuration is becoming more and more attractive compared with the classical central inverter, since it results in better energy yield by realizing distributed maximum power point tracking. Among the existing solutions, an attractive topology consists in a single dc bus bar collector cascaded H-bridge (CHB) inverter. Through the use of a single dc bus bar collector, the CHB inverter presents inherent balanced operation while the multistring PV-system is fully decoupled from the grid-tie inverter. This paper proposes the experimental validation of this structure on a reduced-size single-phase laboratory prototype. Results confirm the interest of the proposed PV multistring architecture.

ETPL PELE - 042	Distributed Power-Generation Systems and Protection

Continuously expanding deployments of distributed power-generation systems (DPGSs) are transforming the conventional centralized power grid into a mixed distributed electrical network. The modern power grid requires flexible energy utilization but presents challenges in the case of a high penetration degree of renewable energy, among which wind and solar photovoltaics are typical sources. The integration level of the DPGS into the grid plays a critical role in developing sustainable and resilient power systems, especially with highly intermittent renewable energy resources. To address the challenging issues and, more importantly, to leverage the energy generation, stringent demands from both utility operators and consumers have been imposed on the DPGS. Furthermore, as the core of energy conversion, numerous power electronic converters employing advanced control techniques have been developed for the DPGS to consolidate the integration. In light of the above, this paper reviews the power-conversion and control technologies used for DPGSs. The impacts of the DPGS on the distributed grid are also examined, and more importantly, strategies for enhancing the connection and protection of the DPGS are discussed.

ETPL PELE - 043	Three-Phase Three-Level Phase-Shifted PWM DC–DC Converter for Electric Ship MVDC Application

A three-phase three-level phase-shifted pulsewidth modulation (PSPWM) dc-dc converter is proposed for electric ship medium-voltage direct current application. Output voltage is controlled by incorporating PSPWM. Gate signals of each phase are phase shifted by $2\pi/3$ from each other. This results in a decrease in output voltage ripple. Major features of the converter include: 1) good dynamic performance under low switching frequency; 2) fault tolerance capability; and 3) plug and play capability. In order to obtain behavioral and performance characteristics of the proposed converter, detailed analytical and hardware in loop simulation studies are carried out. Finally, the viability of the scheme is confirmed through detailed experimental studies on a MW level, 1-kHz prototype developed for the purpose.

ETPL PELE - 044	A Current Control Scheme of Brushless DC Motors Driven by Four-Switch Three-Phase Inverters

Based on the brushless dc motor driven by a four-switch three-phase inverter (FSTPI), a current control scheme is proposed to reduce the current ripple of both the normal conduction region and the commutation region. Assuming c-phase winding is connected to the middle point of a dc-link capacitance, in the normal conduction region when a-phase and b-phase windings conduct, the current of c-phase may not be zero because of c-phase back electromotive force. The proposed strategy adds two regulating vectors into each control cycle based on the traditional PWM scheme, and controls the c-phase current to be zero by controlling the working time of the regulating vectors in each control cycle. In the commutation region, the noncommutated phase or the outgoing phase switch is modulated by comparing the change rate of the incoming and outgoing phase currents to maintain the noncommutated phase current constant. Compared with the traditional current control strategy, good control effect is kept in both the normal conduction region and the commutation region by accurately controlling the working time of the voltage vectors. The proposed strategy does not need to adjust the parameters of the controller, and it is simple and easy to implement. The experimental results prove the correctness and effectiveness of the control strategy.

ETPL PELE - 045	A High Step-up PWM DC-DC Converter with Coupled-Inductor and Resonant Switched-Capacitor

Based on the brushless dc motor driven by a four-switch three-phase inverter (FSTPI), a current control scheme is proposed to reduce the current ripple of both the normal conduction region and the commutation region. Assuming c-phase winding is connected to the middle point of a dc-link capacitance, in the normal conduction region when a-phase and b-phase windings conduct, the current of c-phase may not be zero because of c-phase back electromotive force. The proposed strategy adds two regulating vectors into each control cycle based on the traditional PWM scheme, and controls the c-phase current to be zero by controlling the working time of the regulating vectors in each control cycle. In the commutation region, the noncommutated phase or the outgoing phase switch is modulated by comparing the change rate of the incoming and outgoing phase currents to maintain the noncommutated phase current constant. Compared with the traditional current control strategy, good control effect is kept in both the normal conduction region and the commutation region by accurately controlling the working time of the voltage vectors. The proposed strategy does not need to adjust the parameters of the controller, and it is simple and easy to implement. The experimental results prove the correctness and effectiveness of the control strategy.

ETPL PELE - 046	Power Stage and Feedback Loop Design for LLC Resonant Converter in High-Switching-Frequency Operation

As converter switching frequencies are moving toward megahertz frequencies for high power density, secondary leakage parasitics that were previously negligible have to be considered in mathematical modeling for LLC resonant converters. At high-switching-frequency operation, the power stage design must take secondary leakage inductance into account because it can affect the input–output voltage gain. In addition, the feedback loop design should consider the effect of the time delay caused by the performance limitation of a digital controller to improve the small-signal model accuracy of the converter. Using the proposed power stage and feedback control loop design considerations, the LLC resonant converter can achieve high power conversion efficiency and stability enhancement at high switching frequencies. All the proposed methods are experimentally verified using a 240-W prototype LLC resonant converter operating at 1-MHz switching frequency.

ETPL PELE - 047	A Current-Fed Isolated Bidirectional DC–DC Converter

This paper proposes a current-fed isolated bidirectional dc-dc converter (CF-IBDC) that has the advantages of wide input voltage range, low input current ripple, low conduction losses, and soft switching over the full operating range. Compared with conventional CF-IBDCs, the voltage spikes of the low-voltage (LV) side switches in the proposed converter can be eliminated without additional clamp circuits. The converter adopts the pulse width modulation plus hybrid phase-shift control scheme such that the bus voltage can match the output voltage by means of the transformer. Thus, the current stresses and conduction losses of the converter become lower. In addition, the practical zero voltage switching (ZVS) of the secondary-side switches can be realized by adjusting the phase-shift angle within the secondary side when in light load or no load condition. The operating principles and characteristics including the power transfer, root-mean-square (RMS) current, and soft switching are investigated in detail. Then the design guidelines of inductors are also given. Finally an experimental prototype with 30-60 V input and 400 V/2.5 an output is built to verify the correctness of theoretical analyses.

ETPL PELE - 048	Adaptive Current-Mode Control of a High Step-Up DC–DC Converter

A new adaptive current-mode control of a high step-up dc-dc converter is presented. The converter gives a very high voltage gain without using a transformer and maintains low voltage stress across the power devices. The adaptive controller is formed by combining the existing current-mode control law and an adaptive law that generates the inverse of the load resistance. The structure of the proposed adaptive law is such that the derivative of the estimate is both optimized and bounded. To facilitate the controller design, the derived averaged state-space model of the converter with parasitic elements is used. An approximate stability analysis is carried out to gain some insight into the behavior of the adaptive-controlled system. Some experimental results comparing the performance of the proposed adaptive current-mode controller with that of the existing current-mode controller are also presented.

ETPL PELE - 049	A Modeling and Analysis Method for Fractional-Order DC–DC Converters

This paper proposes a modeling and analysis method for fractional-order dc-dc converters operating in continuous conduction mode (CCM). As an example, a fractional-order boost converter is studied in detail. Instead of using fractional calculus, the method presented here uses a general state vector differential equation to describe the converter. By combining the principle of harmonic balance and equivalent small parameter method, an approximate analytical steady-state solution of the state variables could be obtained. Subsequently, the CCM-operating criterion of the converter is discussed based on the proposed method, and the appropriate parameters are provided to make sure that the fractional-order converter operates in CCM. In addition, a statistical analysis of harmonics is performed, from which the effects of fractional orders on harmonics can be observed. Moreover, numerical simulations are performed using the Adams-Bashforth-Moulton-typed predictor-corrector method and the Oustaloup's-filter-based approximation method. Both the dc components and ripples of the state variables obtained from these two methods are combined with those obtained by the proposed method, and they are in good agreement. Finally, the fractional-order capacitor and inductor are designed and verified by simulations, and on the basis of which experiments of the fractional-order boost converter are carried out to further verify the proposed method.

ETPL PELE - 050	Switching Frequency Dynamic Control for DFIG Wind Turbine Performance Improvement around Synchronous Speed

In a doubly-fed induction generator (DFIG) wind turbine (WT), large thermal and mechanical oscillations occur around synchronous speed due to the nearly zero-frequency current circulating between rotor windings and rotor-side converter (RSC). A switching frequency dynamic control technique is proposed in this paper to overcome the problem. The basic idea is to dynamically reduce the switching frequency during operation so that both the switching losses and dead-time effect of RSC can be reduced around synchronous speed. According to the characteristic that high-frequency pulse width modulation (PWM) harmonics in DFIG decrease significantly with rotor slip, there would be a new space for switching frequency reduction especially around synchronous speed. The reduced of switching frequency is actually determined by a tradeoff between the increase of both the stator current PWM harmonics and speed PWM ripples and the decrease of insulated-gate bipolar transistor temperature. Compared with the conventional technique with constant switching frequency, the new technique can effectively improve the system performance around synchronous speed including not only better thermal behavior and efficiency of RSC but also smaller current total harmonics and speed total ripples in generator. To clarify the method, first, the effects of switching frequency reduction on a DFIG WT system are investigated. Second, the criteria, control scheme, and procedure of the method are presented. Finally, experimental and simulation studies were carried out, and the results validate its feasibility and effectiveness.

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