Reliability of Capacitors for DC-Link Applications in Power Electronic Converters—An Overview

Huai Wang, *Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—DC-link capacitors are an important part in the majority of power electronic converters which contribute to cost, size and failure rate on a considerable scale. From capacitor users' viewpoint, this paper presents a review on the improvement of reliability of dc link in power electronic converters from two aspects: 1) reliability-oriented dc-link design solutions; 2) conditioning monitoring of dc-link capacitors during operation. Failure mechanisms, failure modes and lifetime models of capacitors suitable for the applications are also discussed as a basis to understand the physics-of-failure. This review serves to provide a clear picture of the state-of-the-art research in this area and to identify the corresponding challenges and future research directions for capacitors and their dc-link applications.**

***Index Terms*—Ceramic capacitors, dc link, electrolytic capacitors, film capacitors, power converters, reliability.**

I. Introduction

CAPACITORS are widely used for dc links in power converters to balance the instantaneous power difference between the input source and output load, and minimize voltage variation in the dc link. In some applications, they are also used to provide sufficient energy during the hold-up time. Fig. 1 shows the typical configurations of power electronic conversion systems with dc-link capacitors. Such configurations cover a wide range of power electronics applications, such as in wind turbines, photovoltaic systems, motor drives, electric vehicles and lighting systems. With more stringent reliability constrains brought by automotive, aerospace and energy industries, the design of dc links encounters the following challenges: a) capacitors are one kind of the stand-out components in terms of failure rate in field operation of power electronic systems [1], [2]; b) cost reduction pressure from global competition dictates minimum design margin of capacitors without undue risk; c) capacitors are to be exposed to more harsh environments (e.g., high ambient temperature, high humidity, etc.) in emerging applications and d) constrains on volume and thermal dissipation of capacitors with the trends for high power density power electronic systems [3].

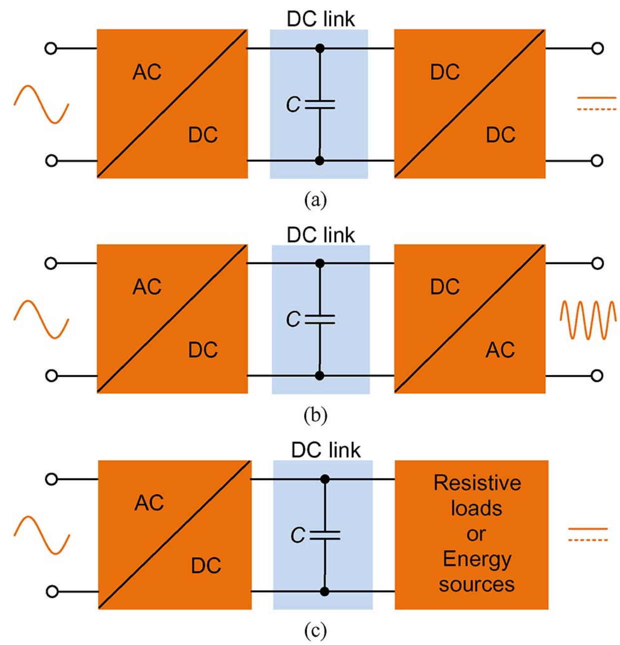

Fig. 1. Typical configurations of power electronic conversion systems with dc-link capacitors: (a) ac–dc-dc or dc-dc-ac power converters with a dc link. (b) ac-dc-ac power converters with a dc link. (c) ac-dc or dc-ac power converters with a dc link.

The efforts to overcome the above challenges can be divided into three categories: a) advance the capacitor technology with improved and pre-determined reliability built in, b) optimal dc-link design solutions based on the present capacitors to achieve proper robustness margin and cost-effectiveness, and c) implementations of condition monitoring to ensure reliable field operation and preventive maintenance. By taking the advantage of the progress in new dielectric materials and innovative manufacturing process, leading capacitor manufacturers have been continuously releasing new generations of products with improved reliability and cost performance. The proper application of these capacitors for specific dc-link design is equally important as the operating conditions (e.g., temperature, humidity, ripple current, voltage) could significantly influence the reliability of the capacitors. Compared to the first category, the latter two are more relevant from the power electronic designers' perspective, which therefore will be reviewed in this paper. Moreover, the comparison of capacitors suitable for dc-link applications are given. The failure modes, failure mechanisms, corresponding critical stressors and lifetime models of them

Manuscript received September 29, 2013; revised December 27, 2013; accepted January 23, 2014. Date of publication February 25, 2014; date of current version September 16, 2014. Paper 2013-PEDCC-713.R1, presented at the 2013 IEEE Energy Conversion Congress and Exposition, Denver, CO, USA, September 16–20, and approved for publication in the IEEE Transactions on Industry Applications by the Power Electronic Devices and Components Committee of the IEEE Industry Applications Society. This work was supported by the Danish Council for Independent Research under Grant 12-131914.

The authors are with the Department of Energy Technology, Aalborg University, DK-9220 Aalborg East, Denmark (e-mail: hwa@et.aau.dk; fbl@et.aau.dk).

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Digital Object Identifier 10.1109/TIA.2014.2308357

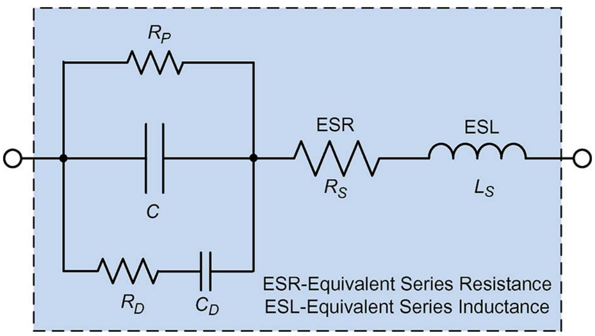


Fig. 2. Simplified lumped model of capacitors.

are also mapped. The challenges and opportunities for future research directions are finally addressed.

II. Capacitors for DC-Link Applications

Three types of capacitors are generally available for dc-link applications, which are the Aluminum Electrolytic Capacitors (Al-Caps), Metallized Polypropylene Film Capacitors (MPPF-Caps) and high capacitance Multi-Layer Ceramic Capacitors (MLC-Caps). The dc-link design requires the matching of available capacitor characteristics and parameters to the specific application needs under various environmental, electrical and mechanical stresses.

Fig. 2 shows a lumped model of capacitors. C, R_s, and L_s are the capacitance, Equivalent Series Resistance (ESR), Equivalent Series Inductance (ESL), respectively. The Dissipation Factor (DF) is $\tan\delta = \omega R_s C$. R_p is the insulation resistance. R_d is the dielectric loss due to dielectric absorption and molecular polarization and C_d is the inherent dielectric absorption [4]. The widely used simplified capacitor model is composed of C, R_s, and L_s. It should be noted that the values of them vary with temperature, voltage stress, frequency and time (i.e., operating conditions). The absence of the consideration into these variations may lead to improper analysis of the electrical stresses and thermal stresses, therefore, also many times unrealistic lifetime prediction.

The property of dielectric materials is a major factor that limits the performance of capacitors. Fig. 3 presents the relative permittivity (i.e., dielectric constant), continuous operational field strength and energy density limits of Al_2O_3, polypropylene and ceramics, which are the materials used in Al-Caps, MPPF-Caps and MLC-Caps, respectively [5]. It can be noted that Al_2O_3 has the highest energy density due to high field strength and high relative permittivity. The theoretical limit is in the range of 10 J/cm^3 and the commercial available one is about 2 J/cm^3. Ceramics could have much higher dielectric constant than Al_2O_3 and film, however, it suffers from low field strength, resulting in similar energy density as that of film.

The three type of capacitors therefore exhibit specific advantages and shortcomings. Fig. 4 compares their performance from different aspects in a qualitative way. Al-Caps could achieve the highest energy density and lowest cost per Joule, however, with relatively high ESRs, low ripple current ratings, and wear out issue due to evaporation of electrolyte. MLC-Caps have smaller size, wider frequency range, and higher operating temperatures up to 200 °C. However, they suffer from higher cost and mechanical sensitivity. The recent release of CeraLink series ceramic capacitors [6] is of interest to extend the scope of MLC-Caps for dc-link applications. It is based on a new ceramic materials of antiferroelectric behavior and strong positive bias effect (i.e., capacitance versus voltage stress). MPPF-Caps provide a well-balanced performance for high voltage applications (e.g., above 500 V) in terms of cost and ESR,

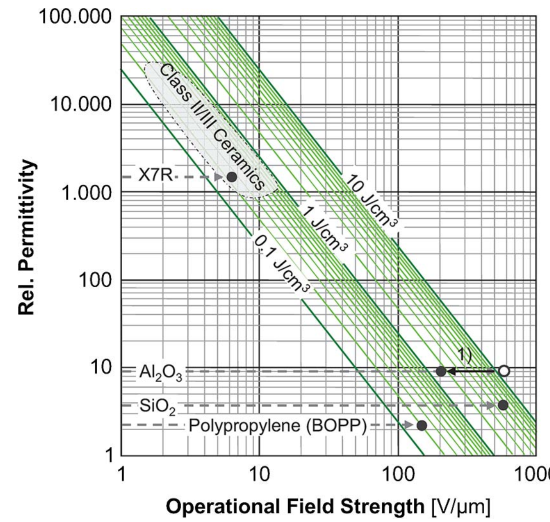


Fig. 3. Energy storage density for various dielectrics (BOPP: Biaxial Oriented PolyproPylene, which is the preferred film material for capacitors rated above about 250 V) [5].

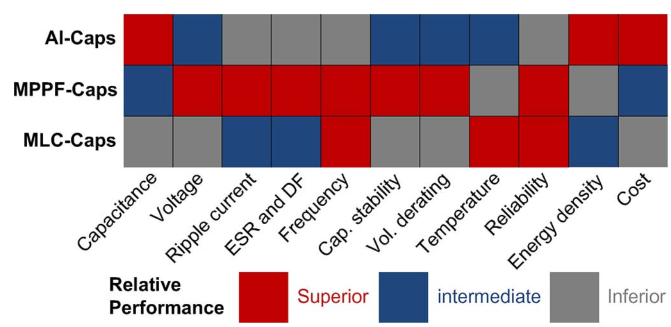


Fig. 4. Performance comparisons of the three main types of capacitors for dc-link applications.

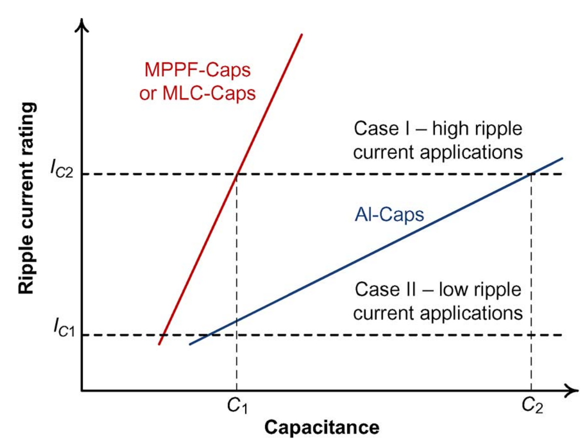


Fig. 5. Capacitance requirement of low ripple current applications and high ripple current applications.

TABLE I
OVERVIEW OF FAILURE MODES, CRITICAL FAILURE MECHANISMS AND CRITICAL STRESSORS OF THE THREE MAIN TYPES DC-LINK CAPACITORS (WITH EMPHASIS ON THE ONES RELEVANT TO DESIGN AND OPERATION OF POWER CONVERTERS)

Cap. type	Failure modes	Critical failure mechanisms	Critical stressors
Al-Caps	Open circuit	Self-healing dielectric breakdown	V_C, T_a, i_C
		Disconnection of terminals	Vibration
	Short circuit	Dielectric breakdown of oxide layer	V_C, T_a, i_C
	Wear out: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Electrolyte vaporization	T_a, i_C
		Electrochemical reaction (e.g. degradation of oxide layer, anode foil capacitance drop)	V_C
MPPF-Caps	Open circuit (typical)	Self-healing dielectric breakdown	V_C, T_a, dV_C/dt
		Connection instability by heat contraction of a dielectric film	T_a, i_C
		Reduction in electrode area caused by oxidation of evaporated metal due to moisture absorption	Humidity
	Short circuit (with resistance)	Dielectric film breakdown	V_C, dV_C/dt
		Self-healing due to overcurrent	T_a, i_C
		Moisture absorption by film	Humidity
	Wear out: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Dielectric loss	V_C, T_a, i_C, humidity
MLC-Caps	Short circuit (typical)	Dielectric breakdown	V_C, T_a, i_C
		Cracking; damage to capacitor body	Vibration
	Wear out: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Oxide vacancy migration; dielectric puncture; insulation degradation; micro-crack within ceramic	V_C, T_a, i_C, vibration

V_C-capacitor voltage stress, i_C-capacitor ripple current stress, i_{LC}-leakage current, T_a- ambient temperature.

capacitance, ripple current and reliability. Nevertheless, they have the shortcomings of large volume and moderate upper operating temperature.

The dc-link applications can be classified into high ripple current ones and low ripple current ones. The ripple current capability of the three types of capacitors is approximately proportional to their capacitance values as shown in Fig. 5. C_1 is defined as the minimum required capacitance value to fulfill the voltage ripple specification. For low ripple current applications, capacitors with a total capacitance no less than C_1 are to be selected by both Al-Caps solution and MPPF-Caps solution. For high ripple current applications, the Al-Caps with capacitance of C_1 could not sustain the high ripple current stress due to low A/μF. Therefore, the required capacitance is increased to C_2 by Al-Caps solution while the one by MPPF-Caps solution is C_1. In terms of ripple current (i.e., ($/A), the cost of MPPF-Caps is about 1/3 of that of Al-Caps [7]. It implies the possibility to achieve a lower cost, higher power density dc-link design with MPPF-Caps in high ripple current applications, like the case in electric vehicles [8].

III. FAILURE AND LIFETIME OF DC-LINK CAPACITORS

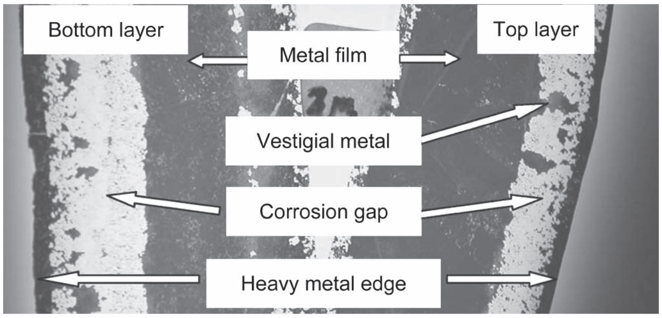
A. *Failure Modes, Failure Mechanisms and Critical Stressors*

DC-link capacitors could fail due to intrinsic and extrinsic factors, such as design defect, material wear out, operating temperature, voltage, current, moisture and mechanical stress, and so on. Generally, the failure can be divided into catastrophic failure due to single-event overstress and wear out failure due to the long time degradation of capacitors. The major failure mechanisms have been presented in [9]–[12] for Al-Caps, [13]–[17] for MPPF-Caps and [18]–[20] for MLC-Caps. Based on these prior-art research results, Table I gives a systematical summary of the failure modes, failure mechanisms and corresponding critical stressors of the three types of capacitors.

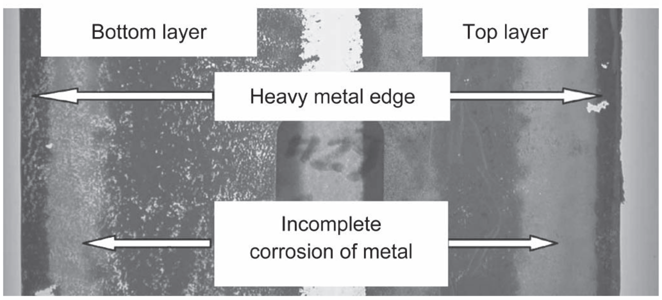
TABLE II
COMPARISONS OF FAILURE AND SELF-HEALING CAPABILITY OF THE THREE TYPES OF CAPACITORS

	Al-Caps	MPPF-Caps	MLCC-Caps
Dominant failure modes	wear out		
	open circuit	open circuit	short circuit
Dominant failure mechanisms	electrolyte vaporization; electrochemical reaction	moisture corrosion; dielectric loss	insulation degradation; flex cracking
Most critical stressors	T_a, V_C, i_C	T_a, V_C, humidity	T_a, V_C, vibration
Self-healing capability	moderate	good	no

Table II shows the comparison of failure and self-healing capability of Al-Caps, MPPF-Caps, and MLC-Caps. Electrolyte vaporization is the major wear out mechanism of small size Al-Caps (e.g., snap-in type) due to their relatively high ESR and limited heat dissipation surface. For large size Al-Caps, the wear out lifetime is dominantly determined by the increase of leakage current, which is relevant with the electrochemical reaction of oxide layer [21]. The most important reliability feature of MPPF-Caps is their self-healing capability [15], [16]. Initial dielectric breakdowns (e.g., due to overvoltage) at local weak points of a MPPF-Cap will be cleared and the capacitor regains its full ability except for a negligible capacitance reduction. With the increase of these isolated weak points, the capacitance of the capacitor is gradually reduced to reach the end-of-life.



(a)



(b)

Fig. 6. Corrosion of the metallized layers of a film capacitor [23]. (a) Separation of metal film from heavy edge by corrosion. (b) Incomplete edge separation by corrosion.

The metallized layer in MPPF-Caps is typically less than 100 nm [22] which are susceptible to corrosion due to the ingress of atmospheric moisture. In [23], the corrosion mechanism is well studied. Fig. 6(a) and (b) show the corrosion of the metallized layers of a degraded film capacitor located in the outer turns and inner turns of the capacitor roll, respectively. It reveals that severe corrosion occurs at the outer layers resulting in the separation of metal film from heavy edge and therefore the reduction of capacitance. The corrosion in the inner layers is less advanced as it is less open to the ingress of moisture. Unlike the dielectric materials of Al-Caps and MPPF-Caps, the dielectric materials of MLC-Caps are expected to last for thousands of years at use level conditions without showing significant degradation [19]. Therefore, wear out of ceramic capacitors is typically not an issue. However, a MLC-Cap could be degraded much more quickly due to the "amplifying" effect from the large number of dielectric layers [19]. In [24], it has been shown that a modern MLC-Cap could wear out within 10 years due to increasing miniaturization through the increase of the number of layers. Moreover, the failure of MLC-Caps may induce severe consequences to power converters due to the short circuit failure mode. The dominant failure causes of MLC-Caps are insulation degradation and flex cracking. Insulation degradation due to the decrease of the dielectric layer thickness results in increased leakage currents. Under high voltage and high temperature conditions, Avalanche BreakDown (ABD) and Thermal RunAway (TRA) could occur, respectively. Fig. 7 shows a study in [18] on the leakage current characteristics of a MLC-Cap with ABD and TRA failure. ABD features with an abrupt burst of current leading to an immediate breakdown, while TRA exhibits a more gradual increase of leakage current.

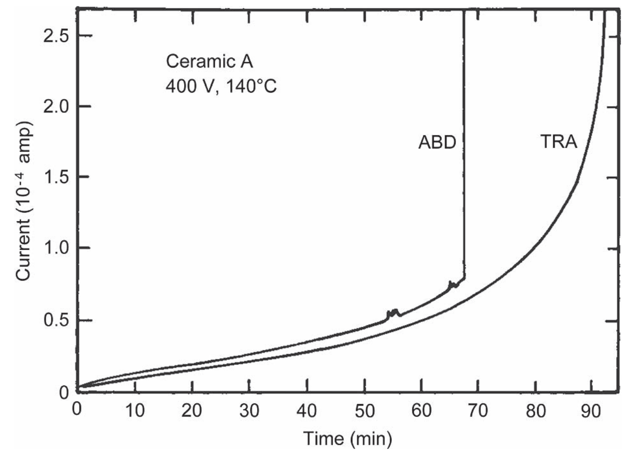


Fig. 7. Leakage current of a barium titanate-based MLC-Cap under high temperature and high voltage stresses (ABD: Avalanche BreakDown, TRA: Thermal RunAway) [18].

B. Lifetime Models of DC-Link Capacitors

Lifetime models are important for lifetime prediction, online condition monitoring and benchmark of different capacitor solutions. The most widely used empirical model for capacitors is shown in (1) which describes the influence of temperature and voltage stress

$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n} \times \exp\left[\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \quad (1)$$

where L and L_0 are the lifetime under the use condition and testing condition, respectively. V and V_0 are the voltage at use condition and test condition, respectively. T and T_0 are the temperature in Kelvin at use condition and test condition, respectively. E_a is the activation energy, K_B is Boltzmann's constant (8.62×10^{-5} eV$/K$), and n is the voltage stress exponent. Therefore, the values of E_a and n are the key parameters to be determined in the above model.

In [25], the E_a and n are found to be 1.19 and 2.46, respectively, for high dielectric constant ceramic capacitors. In [24], the ranges of E_a and n for MLC-Caps are 1.3–1.5 and 1.5–7, respectively. The large discrepancies could be attributed to the ceramic materials, dielectric layer thickness, testing conditions, etc. With the trend for smaller size and thinner dielectric layer, the MLC-Caps will be more sensitive to the voltage stress, implying a higher value of n. Moreover, under different testing voltages, the value of n might be different as discussed in [26].

For Al-Caps and film capacitors, a simplified model from (1) is popularly applied as follows:

$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n} \times 2^{\frac{T_0 - T}{10}}. \quad (2)$$

The derivation of (2) from (1) is discussed in [27]. The model presented by (2) is corresponding to a specific case of (1) when $E_a = 0.94$ eV and T_0 and T are substituted by 398 K. For MPPF-Caps, the exponent n is from around 7 to 9.4 used by leading capacitor manufacturers [28]. For Al-Caps, the value of n typically varies from 3 to 5 [29]. However, the voltage dependency of lifetime for Al-Caps quite depends on the voltage stress level. In [10], instead of a power law relationship, a linear equation is found to be more suitable to describe the impact of voltage stress. Moreover, the lifetime dependence on temperature presented in (2) is an approximation only [30]. In [30] and [31], a lifetime model of electrolytic capacitors is proposed based on the ESR drift due to electrolyte evaporation and loss. The estimation of the ESR is based on the electrolyte pressure and the reduction of the electrolyte volume. The prediction results fit well with the lifetime—temperature relationship shown in (1) (i.e., Arrhenius equation). To obtain the physical explanations of the lifetime model variants from different capacitor manufacturers, a generic model is derived in [32] as follows:

$$\frac{L}{L_0} = \begin{cases} \left(\frac{V_0}{V}\right) \times \exp\left[\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] & (\text{low } \xi) \\ \left(\frac{V_0}{V}\right)^{-n} \times \exp\left[\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] & (\text{medium } \xi) \\ \exp\left[a_1(V_0 - V)\right] \times \exp\left[\frac{E_{a0} - a_0 \xi}{K_B T} - \frac{E_{a0} - a_0 \xi_0}{K_B T_0}\right] & (\text{high } \xi) \end{cases} \quad (3)$$

where a_0 and a_1 are constants describing the voltage and temperature dependency of E_a. ξ and ξ_0 are stress variables (i.e., voltage and/or temperature) under operation and test, respectively. E_{a0} is the activation energy under test. It can be noted that the influence of voltage stress is modeled as linear, power law, and exponential equations, respectively for low voltage stress, medium voltage stress and high voltage stress. Another important observation is that the activation energy E_a is varying with voltage and temperature, especially under high voltage stress conditions. It is in agreement with the observations in [30] that the equivalent values of E_a/K_B are varying under different temperature ranges.

IV. Reliability-Oriented Design for DC-Links

A. DC-Link Design Solutions

As the dc-link capacitors contribute to cost, size and failure of power electronic converters on a considerable scale [1], research efforts have been devoted to either optimal design of dc-link capacitor bank [33] or to the reduction of the dc-link requirement [34]. Fig. 8 shows the main types of dc-link design solutions. The most widely applied solution is the one shown in Fig. 8(a) by selecting Al-Caps or MPPF-Caps as discussed in Section II. Recently, a hybrid design solution composed of both Al-Caps and MPPF-Caps is proposed in [35] as illustrated in Fig. 8(b). A dc link with 40 mF Al-Caps bank and a 2 mF MPPF-Cap are selected for a 250 kW inverter, by taking the advantage of their different frequency characteristics. Fig. 9 compares the ripple current stresses in the Al-Caps bank with and without the additional 2 mF film capacitor. By adopting this solution, the reliability of the Al-Caps bank is to be improved due to reduced current stresses. Another research direction is to reduce the energy storage requirement in the dc link so that Al-Caps could be replaced by MPPF-Caps to achieve higher level of reliability without considerably increase the cost and volume. For example, the concept of Fig. 8(c) is to synchronize the current i_{DC1} and i_{DC2} by additional control scheme to reduce the ripple current flowing through the dc-link capacitor [36]. This solution is especially applicable for the application when there is specific relationship in the operating frequency between the two converters connected to the dc link. The concept of Fig. 8(d) and (e) is to introduce an additional ripple power port apart from the dc link [34] and [37]. These two solutions could reduce the overall energy storage requirement of the dc link as the study cases demonstrated in [34] and [37], [38]. The advantage of the series voltage compensator solution in [34] is that the power capacity of the compensator is much lower than that of the parallel circuit shown in Fig. 8(d). It is due to very low voltage stresses on the active devices inside the compensator. Fig. 8(f) shows the sixth type of dc-link solution, of which the conventional dc-link capacitors are directly replaced by an energy buffer with high energy buffering ratio. The energy buffering ratio is defined as the ratio of the energy that can be injected and extracted from the dc link in one cycle to the total energy stored in the dc link [39]. An interesting stacked switched capacitor circuit is proposed in [39] to perform the function of an energy buffer, making it possible to achieve over 90% energy buffering ratio.

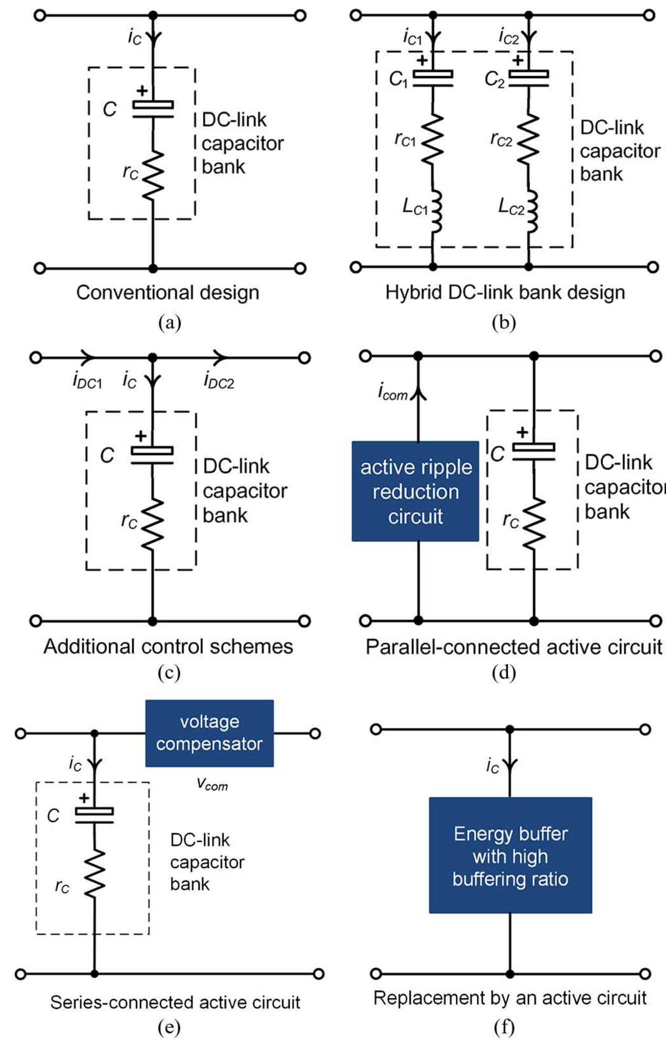


Fig. 8. Main types of solutions for dc-link design.

The active dc-link solutions shown in Fig. 8(d)–(f) open the opportunities to replace the E-Caps by MPPF-Caps with

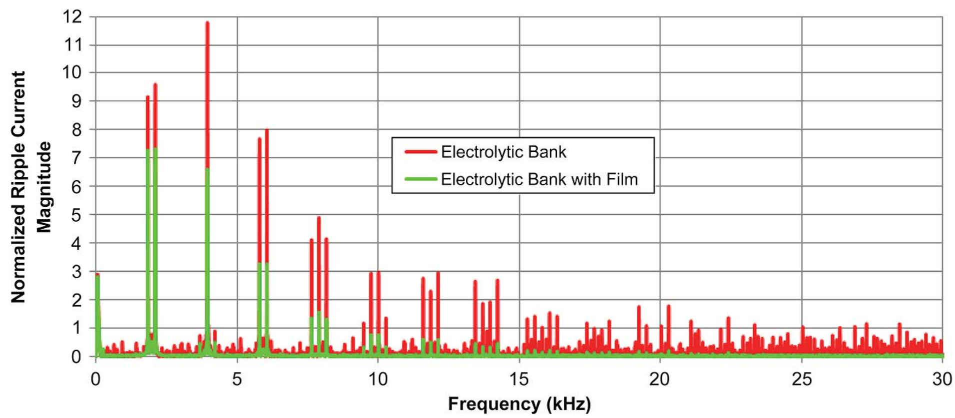


Fig. 9. Ripple current stresses of the 40 mF Al-Caps bank with or without an additional 2 mF film capacitor for a 250 kW inverter application discussed in [35].

a comparable size and cost. The reliability of the capacitor part is improved, however, the additional circuits and control schemes will induce new potential failures in the dc-link part. Therefore, a comprehensive evaluation of the reliability of the whole dc-link part is needed to quantify the impact of these new solutions.

B. Reliability-Oriented Design Procedure for DC Link

Besides the possibilities brought by innovative dc-link solutions, a reliability-oriented design procedure could provide further potentials to build the reliability into the dc link. Fig. 10 presents a reliability-oriented design procedure for dc links. Highlighted areas indicate where further research efforts are expected. The key steps are discussed as follows:

a) Higher level definition: The dc-link design depends on the converter level specifications (e.g., power rating, voltage level, and lifetime target), circuit topologies, control methods, and design constrains on other components. For voltage source converters or inverters, the dc link is capacitive composed of capacitors, while for current source converters or inverters, the dc link is inductive mainly composed of inductors [40]. The capacitive type is more widely used than the inductive one due to the popularity of voltage source converters and inverters in various applications. One of the reasons is that capacitors generally have higher energy density than that of inductors. The selections of other components also affect the sizing of dc-link capacitors. For example, the choice of the input side inductor in an ac variable-frequency drive has significant impact on the lifetime of its dc-link capacitor bank, as studied in [31] and [45]. It reveals that a higher inductor value (i.e., a higher line impedance) is beneficial to the improvement of the capacitor bank lifetime or to the reduction of the required capacitance. Therefore, it is essential to have a system level scope. From the reliability perspective, it is important to allocate the system level reliability target to each important components, including the dc-link capacitors.

b) DC-link level definition: Based on the converter level specifications, the major design constrains of dc link are dc-link voltage level, limit of dc-link voltage ripple, volume, cost and lifetime. Another important aspect of the definition is the environmental conditions (e.g., ambient temperature profile, humidity profile) [41]. Based on the above information, the ripple current stress can be calculated and therefore the required minimum capacitance can be preliminarily determined. An accurate ripple current stress analysis of dc-link capacitors is crucial to both the selection of proper capacitors and the lifetime prediction of them. The detailed derivation of the ripple current spectrums for a three phase inverter and for general voltage source inverters are presented, respectively in [42] and [43]. The challenges in the ripple current stress analysis in real-world applications lie in twofold: firstly, in applications like photovoltaic (PV) inverters or wind turbines, the solar irradiance profile or wind speed profile together with the ambient temperature profile have significant impact on the ripple current stress of dc-link capacitors, which should be taken into account; secondly, the degradation of the dc-link capacitors and other components in power electronic converters (e.g., switching devices) could in turn affect the ripple currents flowing through dc-link capacitors. More research efforts are expected to tackle those issues to achieve more realistic ripple current stress analysis.

c) Capacitor type selection: Depending on the application and the calculated ripple current stress and required minimum capacitance, as illustrated in Figs. 5 and 8, a preliminary selection on the capacitor type and the corresponding dc-link solution can be determined.

d) Electrical analysis and design: This step comes to the selection of specific capacitors and the design of the dc-link bank if either multiple capacitors are needed or they will exhibit better performance than single one [33]. The capacitor bank design with a low parasitic inductance is desirable to reduce the chance of overvoltage of both the capacitors and the relevant switching devices [44]. Moreover, it is important to consider the variation of electrical parameters with time and with operation conditions. For example, a lumped capacitor impedance model is presented in [45] which differentiates the three major sources of the ESR. Therefore, the ESR variation with ripple current frequency and temperature can be taken into account in circuit level simulations, allowing a more accurate thermal stress estimation in the next step.

e) Thermal analysis and design: As shown in Table II, temperature is one of the most important stressors that influence the reliability of capacitors. Therefore, besides the electrical

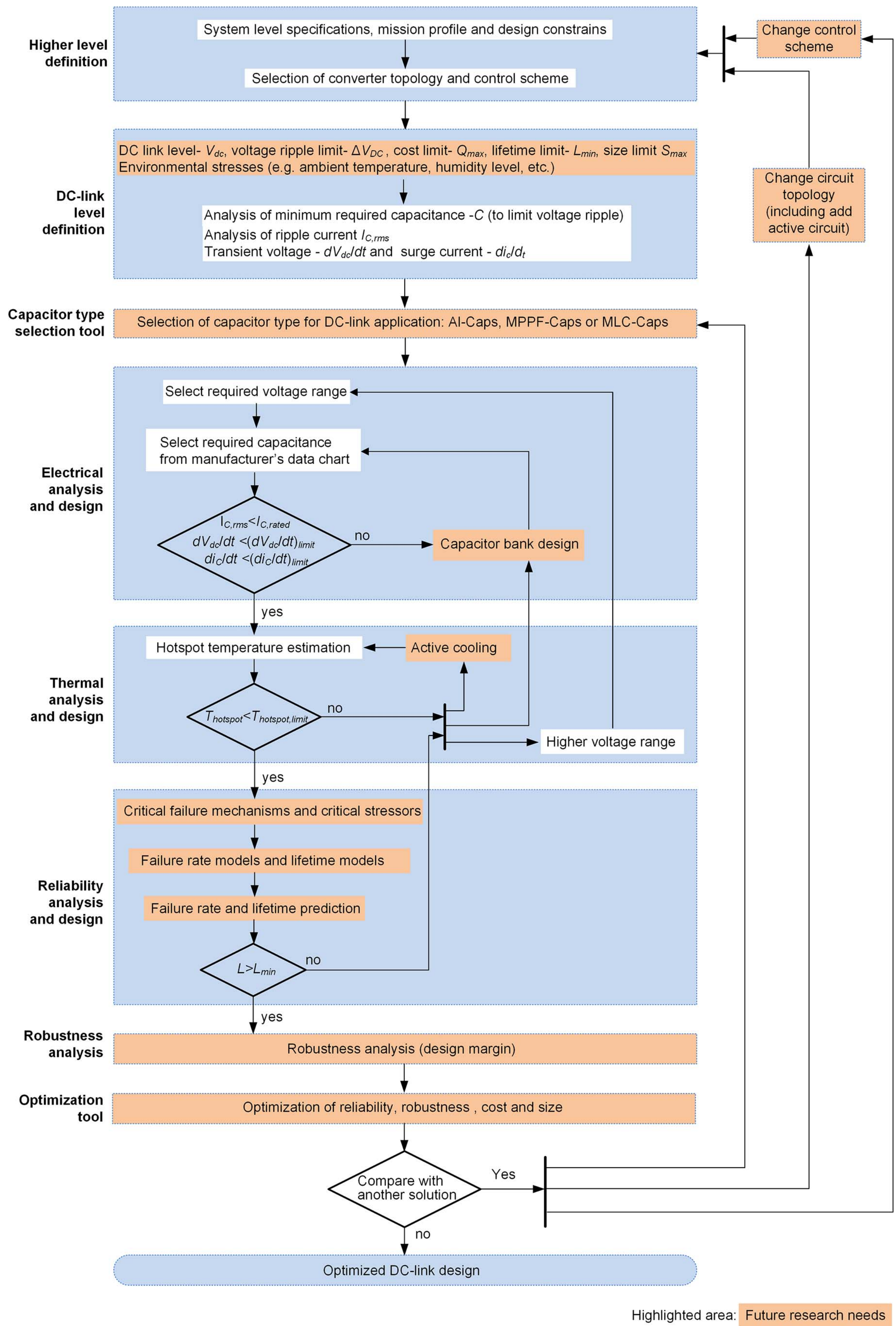


Fig. 10. Reliability-oriented design procedure for capacitors in dc links.

stress analysis [33], thermal stress analysis is equal important to the choice of capacitors and the design of dc-link banks. The connection between the electrical stress analysis and thermal stress analysis is the thermal impedance network of the capacitor of interest. The thermal impedance of a single electrolytic capacitor and a numerical heat transfer model of capacitor banks have been investigated in [46] and [47], respectively. In [47], the heat transfer dependence on capacitor spacing and capacitor location (i.e., center capacitors and side capacitors) are also studied. In [48], the thermal stress of the dc-link capacitors applied to a PV inverter is analyzed under different ambient temperature and solar irradiance level. The accuracy of this study quite depends on the accuracy of the obtained thermal impedance. Another option is to directly measure the hotspot (or close to) temperature by using integrated thermal couplers when the capacitors are available for preliminary evaluation. Active cooling methods could also be applied to certain types of capacitors to reduce the hotspot temperature and therefore extend the lifetime of the capacitors [48]. The penalty of the cooling system is the additional cost, size, weight and potential new failures in the cooling system.

f) Reliability analysis and design: This step covers the lifetime prediction of the pre-selected capacitors based on the failure mechanisms and corresponding lifetime models. As discussed in Section III, these are also the highlighted areas where more research efforts are needed to obtain better understanding on the failure mechanisms, new physics-of-failure based lifetime models and more realistic lifetime design and prediction.

g) Robustness analysis and optimization: The final steps of the design procedure are the design margin (i.e., robustness) analysis [49] and multi-objective optimization on reliability, robustness, cost and size of the dc-link design solution. Different dc-link design solutions, and alternative topologies and control schemes may also need to be evaluated and compared to reach to the final design solution.

While the above design procedure provides a systematic way to select the dc-link capacitors with optimized cost, size and lifetime, it may be still not easy to be applied since its high level of complexity as well as the needs for further research in some of the key steps highlighted in Fig. 10. Among others, the research effort needed is to develop user-friendly software tools that can implement the procedure, so that the power electronic designers can practically apply it in a much easier way.

V. Condition Monitoring of DC-Link Capacitors

Besides the lifetime prediction and reliability-oriented design, condition monitoring is another important action to improve the reliability of dc-link capacitors for critical applications. Of course condition monitoring may entail important investments in terms of devices, sensors and control scheme. All of them shall be evaluated in terms of cost related to the specific application. Table III shows the typical end-of-life criteria and degradation precursors for Al-Caps, MPPF-Caps, and MLC-Caps.

Impressive research work have been done on the condition monitoring of Al-Caps [50]–[54]. Fig. 11 shows the impedance

TABLE III
Typical End-of-Life Criteria and Condition Monitoring Parameters

	Al-Caps	MPPF-Caps	MLC-Caps
Failure criteria	*C*: 20% reduction ESR: 2 times	*C*: 5% reduction DF: 3 times	*C*: 10% reduction $R_p < 10^7\ \Omega$ DF: 2 times
Degradation precursors	*C* or *ESR*, or both	*C*	*C*, R_p

DF - Dissipation Factor; R_p – insulation resistance.

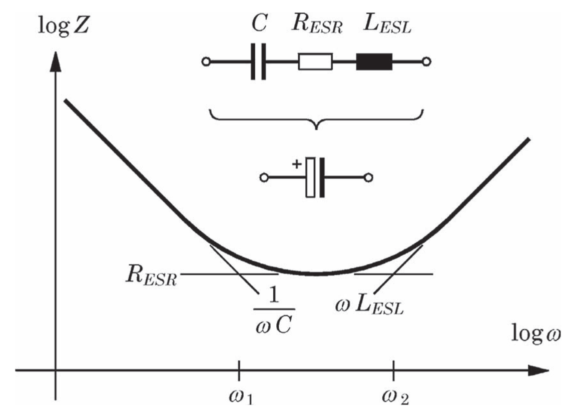


Fig. 11. Impedance characteristics of capacitors [53].

characteristics of capacitors. In the low frequency range $(\omega < \omega_1)$, the impedance is approximated to ωC. In the medium frequency range $(\omega_1 < \omega < \omega_2)$, the impedance is dominated by the ESR. Therefore, by extracting the voltage and/or current information in the respective frequency ranges, the capacitance and ESR can be estimated.

There are two main principles for ESR estimation: a) $ESR = V_C/I_C$ where V_C and I_C are the Root-Mean-Square (RMS) values of the capacitor voltage and capacitor current in the ohmic region (i.e., $\omega_1 < \omega < \omega_2$, typically 5–10 kHz) [50]–[52]. The case temperature of the capacitor is usually measured to compensate the temperature dependence of ESR. This method requires two bandpass filters, which should have sufficient bandwidth to extract the frequency components of interest. At the same time, the frequency components below ω_1 shall be rejected sufficiently. b) $ESR = P_C/I_C^2$ where P_C is the average power dissipated in the capacitor and I_C is the RMS current of the capacitor [53], [54]. This method does not require specific bandpass filters. The introduction of the sensor in the capacitor current path may not be desirable in practical applications due to its stray inductance.

The main applied principle to estimate the capacitance of both Al-Caps and MPPF-Caps is $C = (\int i_c dt)/\Delta v_c$, where i_c is the capacitor current and the Δv_c is the capacitor voltage ripple. In [55], the continuous condition monitoring of MPPF-Caps for an aerospace drive application is presented. To avoid the use of current transducer in series with the dc-link capacitor, the dc-link current i_c is calculated by the difference between the input current of the motor drive and the input current of the inverter. The measurement system should have a wide bandwidth to capture all of the harmonics of the dc-link voltage ripple (triangular) and have a fast sampling rate.

In [56], an off-line prognostics method for MLC-Caps is presented in which the insulation resistance and capacitance are measured. The methodology is based on the parameter residual generated by the difference between the measured capacitance and its estimation. The method may be difficult to be implemented for online condition monitoring.

VI. Conclusion

This paper has given an overview on the reliability aspects of three types of capacitors for dc-link applications in power electronics. Failure modes, failure mechanisms and lifetime models of the capacitors are briefly discussed. Reliability-oriented design approach and condition monitoring methods for dc-link capacitors are presented. Based on this literature review, the following challenges and suggested research directions are addressed:

Challenges—a) uncertainties in the mission profile of specific applications, which may lead to unrealistic component level stress analysis; b) variations of the constant parameters in lifetime models (e.g., activation energy, voltage acceleration factor) with external stresses, which require resource-consuming accelerated lifetime testing to investigate them and may not be economic viable to some extent; c) well established lifetime models take into account the stressors of voltage, ripple current and temperature only.

Suggested Research Directions—a) real time capacitor electrical models that takes into account the operating points (e.g., voltage, ripple current, ambient temperature, frequency, time, etc.) which will contribute to more accurate stress analysis of dc-link capacitors; b) investigation into the coupling effect among various stressors on the lifetime of capacitors; c) the reliability of different dc-link solutions shall be strictly examined as new circuits or software algorithms are introduced which could be the new sources of failure; d) new non-invasive condition monitoring methods with less realization effort and higher estimation accuracy.

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Huai Wang (S'07–M'12) received the B.Eng. degree in electrical and electronic engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2007, and the Ph.D. degree in electronic engineering from the City University of Hong Kong, Kowloon, Hong Kong, in 2012.

He has been with Aalborg University, Aalborg, Denmark, since 2012, where he is currently an Assistant Professor with the Department of Energy Technology. He was a Visiting Scientist with the Massachusetts Institute of Technology, Cambridge, MA, USA, in 2013. He was with the ABB Corporate Research Center, Baden, Switzerland, in 2009. He has contributed over 50 journal and conference papers and filed three patents. His current research interests include the reliability of dc-link capacitors, reliability of power electronic systems, high-voltage dc–dc power converters, time-domain control of converters, and passive components reduction technologies.

Dr. Wang is a recipient of five paper awards and project awards from industry, IEEE, and the Hong Kong Institution of Engineers. He has served as a Guest Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS Special Issue on Robust Design and Reliability in Power Electronics, and as a Session Chair for various conferences on power electronics.

Frede Blaabjerg (S'86–M'88–SM'97–F'03) received the Ph.D. degree from Aalborg University, Aalborg, Denmark, in 1992.

From 1987 to 1988, he was with ABB-Scandia, Randers, Denmark. He is with Aalborg University, where he became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. He has been a part time Research Leader with the Research Center Risoe in wind turbines. From 2006 to 2010, he was the Dean of the Faculty of Engineering, Science, and Medicine and became a Visiting Professor with Zhejiang University, Hangzhou, China, in 2009. His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics, and adjustable-speed drives.

Prof. Blaabjerg received the 1995 Angelos Award for his contributions to modulation technique and the Annual Teacher Prize at Aalborg University. In 1998, he received the Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society. He has received 15 IEEE Prize Paper Awards and another Prize Paper Award at PELINCEC Poland in 2005. He received the IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010 and the IEEE William E. Newell Power Electronics Award 2014. He has received a number of major research awards in Denmark, including the largest individual Danish research award—Villum Kann Rasmussen Annual Award for Technical and Scientific Research in 2014. He was the Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2006 to 2012. He was a Distinguished Lecturer of the IEEE Power Electronics Society from 2005 to 2007 and of the IEEE Industry Applications Society from 2010 to 2011. He was the Chairman of EPE in 2007 and PEDG, Aalborg, in 2012.