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Different Switchover-strategies for Load Balancing in Future Aircraft

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Abstract: Saving weight in aircraft is the major challenge to reduce fuel consumption and decrease the running costs. The electrical distribution system in aircraft is oversized and shows potential for optimization. An inflexible point-to-point supply of loads is the state-of-the-art technology in aircraft nowadays. Because the wiring is rigid, it is not possible to connect loads to different power feeders when the aircraft is in flight. New technologies are required for handling the increasing demand for electricity on board aircraft. Two concepts — phase balancing and feeder balancing — which lead to an energy-efficient power supply network, are introduced. Both methods use intelligent switching nodes with power semiconductor devices, such as MOSFETs. The power transistors are chosen in such a way that they are slightly above the limits for forward current, blocking voltage and switching frequency. The number of switching operations that produce overvoltages and overcurrents in the electrical grid increases if the concepts that have been presented are used. To ensure that the transistors operate in their safe operating area, snubber circuits are used. Since the switching nodes bring in additional weight, these snubbers have to be designed in such a way that they are sufficiently light. Based on an analytical examination of switching ohmic-inductive and ohmic-capacitive loads, different switching strategies for reducing the negative switching effects are introduced. Computer simulation results are presented and evaluated.

Keywords: Feeder Balancing, More Electric Aircraft, Phase Balancing, Switching strategy

Različne preklopne strategije uravnoteženja bremena v letalih prihodnosti

Izvleček: Prihranek pri teži je največji izziv pri varčevanju z gorivom in zniževanju stroškov v letalu. Električen sistem v letalu je predimenzioniran in ponuja možnosti optimizacije. Trenutno stanje tehnike v letalstvu je napajanje bremena po sistemu od točke do točke. Zaradi togega ožičenja posameznega bremena med letom ni mogoče napajati z različnimi viri, zato so potrebe nove tehnologije, ki bodo sposobne dovajati vedno večje potrebe po energiji. Predstavljena sta dva koncepta – balansiranje faze in balansiranje vira –, ki vodita v energijsko učinkovit napajalni sistem. Obe metodi uporabljata preklopne vozle z močnostnimi polprevodniškimi elementi, kot je MOSFET. Močnostni tranzistorji so dimenzionirani le nekoliko nad mejnimi prevodnimi tokovi, blokirnimi napetostmi in preklopnimi frekvencami. Pri uporabi predstavljenih konceptov se poveča število preklopnih operacij, ki povzročajo prenapetosti in nad tokove. Za zagotavljanje delovanja tranzistorjev v varnem območju delovanja se uporabljajo blažilna vezja. Ker preklopna vozlišča prinašajo dodatno težo je potrebno blažilna vezja izvesti s čim manjšo težo. Na osnovi analitičnih raziskav ohmsko induktivnih in ohmsko kapacitivnih bremen so predstavljene različne preklopne strategije za zmanjševanje negativnih preklopnih vplivov. Predstavljene in ovrednotene so računalniške simulacije.

Ključne besede: balansiranje vira, električna letala, balansiranje faze, preklopne strategije

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1 Introduction

The trend in aviation technology is to substitute hydraulic, pneumatic and mechanical systems with electrical ones. This, however, increases the demand for electrical power on board aircraft and is called 'More Electric Aircraft' [1]. Additionally, the consumption of electrical energy rises as passenger comfort increases. In order to handle the higher demand for power, while keeping the weight of the aircraft low, the electrical power supply system has to be optimized. This can be done by implementing a high-voltage-DC bus and a multifunctional fuel cell system [2]. Electrical load analyses have shown the possibility of reducing the weight in the electrical distribution system [16].

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The Institute of Electrical Power Systems of Helmut Schmidt University is conducting research on 'Flexible and energy-efficient aircraft power supply systems'. In this project, new aircraft architectures for feeder and phase balancing are being developed. These methods are aimed at optimizing the current power supply systems. The phase balancing method intends to reduce the return current and leads to a smaller electric structure network (ESN) in new aircraft fuselage made of carbon fibre-reinforced materials (CFRP). The feeder balancing method symmetrises the currents flowing through the power feeders so as to reduce the diameters of cables. Both methods use intelligent switching nodes. At these nodes, the loads can respectively be connected to different phases and power feeders. Therefore, a solid state power controller (SSPC) can be used. An SSPC combines semiconductor and microcontroller technology and works as a monitoring and protection device [3]. State-of-the-art SSPCs prevent overcurrents and overvoltages by controlling the slope of the gate voltage [4]. As a result, the transistors function in the linear mode instead of the switching mode. This method increases losses, which are normally accepted, because switching does not occur very often. However, because switching operations increase in aircraft when maintaining a symmetrised system, the effects of switching have to be analysed. Special components can be added in order to protect the switching node, reducing the negative effects. These can be TVS diodes and snubber circuits.

Another option is a software-controlled solution controlling the switching moments. The switching nodes can be equipped with voltage and current measurement devices, which enable them to follow a specific switching strategy. Assuming that the loads can be represented as a series connection of a resistor and an energy storage device, an analytical examination has been carried out to devise different switching strategies with the aim of reducing overvoltages and overcurrents. Therefore, the quality of the power supply remains high. Different switching strategies have been simulated and compared.

2 Modern concepts using switching nodes

The standard bus voltage of commercial aircraft is 115 V (line-to-ground) in a three-phase system. Electrical generators transmit the power to the primary electrical power distribution centre (PEPDC). The PEPDC supplies flight-critical and consumer loads via secondary power distribution boxes (SPDB). SPDB are connected to loads with currents smaller than 15 A. Most of the power feeders in aircraft are made of aluminium. The return path for the electric current does not use cables, but instead uses the conductive fuselage. Since the fuselage is made of aluminium, the voltage drop is very low. Two methods, aimed at increasing the performance of the electrical grid, are (1) phase balancing and (2) feeder balancing. If a route fails, these methods provide enough opportunities for supplying a load from another cable. This redundancy can increase the availability of the consumer loads and make the electrical grid more tolerant of failure. It is assumed that only cabin and cargo loads are switchable loads, because these loads are non-critical flights loads.

2.1 Phase balancing

Phase balancing is aimed at reducing an asymmetric load of a three-phase feeder. This method becomes advantageous when aircraft manufacturers start to use CFRP materials instead of aluminium for the fuselage of aircraft. CFRP has a lower conductivity than aluminium, which makes it necessary to integrate a conductive ESN into the fuselage for the return current. If there is an asymmetry in a three-phase system, the return current increases, which enhance the voltage drops over the structure [5]. The single-phase loads in the SPDBs can be equipped with threefold-switches, allowing the loads to be connected to either one of the three phases (A, B or C) of a feeder. Through this new approach, the loads can be reallocated in real-time during the flight, allowing for minimization of the return current flowing through the ESN of the aircraft. The reallocation of the cabin and cargo loads is a mixed-integer non-linear optimization problem. It can be solved for instance using genetic algorithm. The objective function of the optimization problem should aim at achieving a symmetric three-phase system. This can be achieved by an objective function "minimize the sum of the negative and zero sequence components". To receive a symmetric three-phase system with a small return current, loads have to be reallocated and switched from one phase to another one. Since switching effects in aircraft increase, because of the application of phase and/or feeder balancing, optimal switching strategies have to be developed to minimize negative switching effects.

During the changeover to another phase, the load is not supplied for a short period, depending on the switching strategy. Aircraft loads have to handle a time of several milliseconds without an energy supply. Nevertheless, the changeover time ought to be small. Because the generators which supply different areas of the aircraft can have different frequencies, computation of phase balancing is limited to each generator of the aircraft to ensure that different grids are not connected. Fig. 1 shows a three-phase generator and exemplary

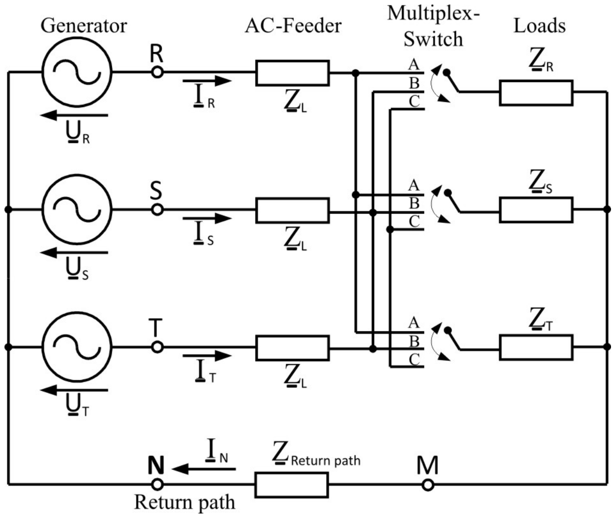

Figure 1: Using threefold-switches for phase balancing of power feeders

three single-phase loads each with a threefold-switch. Every phase of a three-phase feeder has to be connected to each threefold-switch to allow phase balancing. Phase balancing is a large combinatorial optimization problem and non-linear. Because the loads are locally distributed in the aircraft the objective function cannot just assume a virtual ground point where all loads are connected to. This would only lead to a small return current in the front of the aircraft where all currents are added up. Within the ESN higher return current can appear. In order to ensure that phase balancing is not increasing the return current in some locations of the ESN, the actual structure of the ESN has to be taken into account. Fig. 2 shows a more realistic structure of the ESN. It also shows that a threefold switch can supply several loads. In many cases these loads are connected to different grounding point inside the aircraft. Knowing the load currents, phase shifts and the grounding points allows a more effective phase balancing.

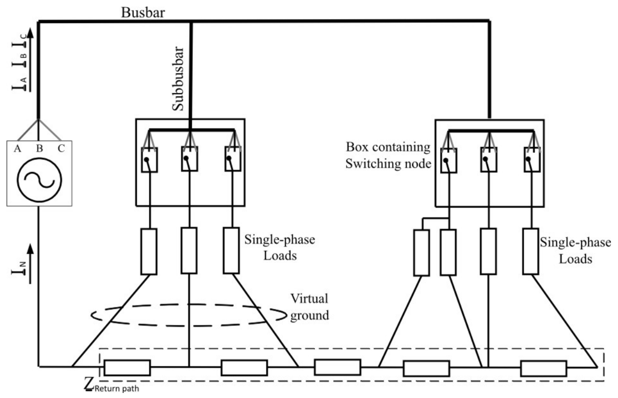

Figure 2: Phase Balancing concept considering the actual structure of loads, switches and the return structure

2.2 Feeder balancing

Because of the high availability, a SPDB is supplied from more than one feeder. The loads in conventional aircraft are allocated with a rigid wiring based on the findings of electrical load analysis. The size of the feeders has to be determined based on the maximum current appearing on the feeder during the flights. Measurements have proved that the power demand of loads vary through the different feeders and that most of the time, the different feeders do not conduct the same current. This non-concurrence facilitates a high optimization potential for feeder balancing. Feeder balancing allows a reduction in the feeder diameter and this saves weight. This is accomplished by switching loads between different feeders (see Fig. 3) to receive a symmetric feeder network, making unused feeder capacities unnecessary [5]. For realizing this in practice, intelligent switching nodes are implemented in aircraft. Such implementation, with the ability to lead all feeders to the single loads, allows for a high granularity. A drawback is the high number of multiplex switches that are needed and the additional cable length. A possible compromise can be reached between the switching options and the additional cable length by leading all passing feeders to the switching node. The feeder balancing concept can be transferred to the DC network of an aircraft.

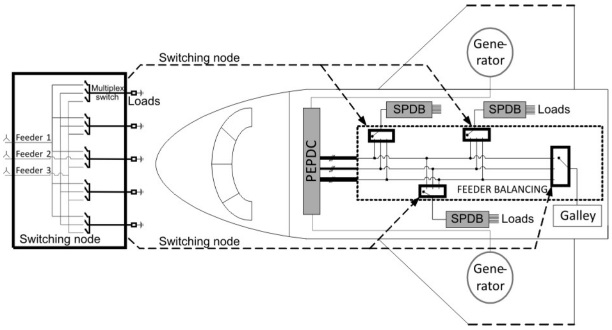

Figure 3: Implementation of switching nodes for smart feeder balancing on board aircraft

Table 1 shows an example electric load analysis of two poorly utilized power feeders reaching their individual maximum current of 25 A and 20 A in different flight phases. If feeder balancing is used and it is assumed that both feeder currents can be distributed equally on the two feeders the highest appearing current will be reduced to 15 A.

3 Switching operations in aircraft ac-electrical grid

In the analytical examination of switching operations, it is assumed that loads can be idealized by a connection

Table 1: Example of poorly utilized power feeder showing potential for current reduction with feeder balancing

Ground / Flight phase	Ground operations	Climb	Cruise	Descent	Highest current
Feeder 1 Cabin	2 A	5 A	25 A	5 A	25 A
Feeder 2 Cargo	20 A	5 A	5 A	5 A	20 A
Average current	11 A	5 A	15 A	5 A	15 A

in series of either an ohmic resistance R with an inductor L, or an ohmic resistance with a capacitor C. Based on this assumption, the formula for the transition voltages and currents have been explained and switching strategies have been developed. After this, the different strategies have been tested via simulation on different kinds of loads. Only loads connected to SPDBs are considered. Heavy inductive loads are directly supplied from the PEPDC. Motors in aircraft with a variable frequency use frequency-variable drives

3.1 Analytical examination

Switching ideal ohmic resistors does not produce any over-voltages or overcurrents. However, this changes when energy storage devices are present. Because switching operations change the energy level of electrical circuits, they cause a transition from the old to the new state. Switching a DC voltage at a capacitor leads to overcurrents when it is turned on if the input voltage is different from the capacitor voltage. Turning a DC current off at an inductive load leads to overvoltages. Switching of a sinusoidal AC voltage, as on board aircraft, has additional effects. The mathematical derivation of the transition current after the turn-on moment is described in detail in [6]. The basic circuit with the two load types is illustrated in Fig. 4. The load can be switched to either phase A or B, depending on the gate signals (Gate A and Gate B). Activating both gate signals would lead to a short circuit.

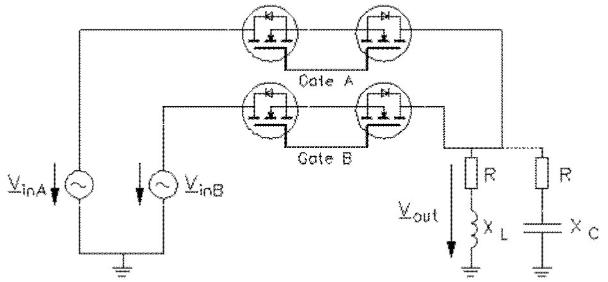

Figure 4: Basic circuit for simulation allowing single-phase loads to be connected to either phase A or phase B of a feeder

3.1.1 Switching operations at ohmic-inductive loads

In contrast to switching a DC voltage, the transition process depends on the instantaneous value of the AC voltage at the moment of switching. When we consider a simple circuit with an inductor and a resistor, it leads to findings which can also be used for current-dependent inductors like transformers or chokes with an iron core [7]. The voltage produced by a generator is given by the formula:

$$v = \hat{v} \cdot \sin(\omega t + \varphi_0)$$

in which $\hat{v}$ is the peak voltage and ω is the angular frequency. The switching operations start at the time t=0. The initial phase φ_0 determines the height of the voltage at the moment of switching. If φ_0 =0, then the voltage is switching at its zero-point. The switching operation is carried out at the maximum value of the voltage if φ_0 =90°. The current required after it is switched on can be calculated using the convolution integral and Laplace-Transformation:

$$i(t) = \frac{\hat{v}}{\sqrt{R^2 + \omega^2 L^2}\left[\sin \omega t + \varphi_0 - \varphi) - \sin(\varphi_0 - \varphi) \cdot e^{\frac{t}{\tau}}\right]}$$

with the time constant $\tau = \frac{L}{R}$ and the phase shift $\varphi = \frac{\arctan\ \omega L}{R}$. The examination of this formula shows that the alternating current component is superposed with a decreasing direct current component. The height of this DC component depends on the initial phase φ_0. The highest current appears when the zero-point of the voltage is switched in. The current can become at the most twice as high as the nominal current. If it is switched in such a way that φ_0 = φ, then the steady state is immediately reached.

Switching an inductive load off, leads to high overvoltages, which can be calculated by Lenz's law:

$$|V_{OUT}| = L\frac{d_i}{d_t}$$

3.1.2 Switching operations at ohmic-capacitive loads

Capacitive loads in an aircraft can be, for example, super-capacitors, DC-DC and DC-AC converters. When it is turned on, a discharged capacitor acts like a short circuit, whereas the current is only limited by the ohmic component. Assuming the voltageis switched on at t=0 to an ohmic-capacitive load, the transition current is:

$$i(t)=\frac{\hat{v}}{R^2+\frac{1}{(\omega\cdot C)^2}}\cdot\left[\cos(\omega t+\varphi_0-\varphi)+\frac{1}{R\omega C}\sin(\varphi_0-\varphi)\cdot e^{\frac{t}{\tau}}\right]$$

with the time-constant τ = RC and the phase shift φ =artcan(RωC). The DC component in the current resulting from switching capacitive loads is a negligible factor. A capacitive load producing a high DC component has, at the same time, a high damping, which leads to a low current [6]. At the moment when it is turned on, the discharged capacitor acts like a short circuit and the current is:

$$i(t=0)=\frac{\hat{v}}{R}\sin\varphi_0$$

This formula considers a discharged capacitor. During the changeover operations for phase or feeder balancing, the loads can be loaded. Depending on the initial phase, a voltage difference occurs between the load voltage and the input voltage. In the worst case, the voltage difference is twice as high as the input voltage. This leads to high inrush currents.

3.1.3 Worst-case scenario

Without using a switching strategy, the power switches and all protection devices have to be designed to withstand the overvoltages and overcurrents that appear when the switching operation is at its worst. To illustrate the different transition processes and to test different switching strategies, a simulation model has been built. The simulation results show the changeover from phase A to phase B. The resultant figures show in the upper part the input voltage V_{inA} and the 120° delayed input voltage V_{inB}. The corresponding gate signals Gate A and Gate B have also been plotted to illustrate the switching moments. The lower part of the figure illustrates the switching effects by showing the output voltage V_{OUT} and the current I. To compare the different switching strategies, the same parameters are used for the current and power factor. Fig. 5 shows the simulation result of a worst-case scenario with an ohmic-inductive load. The load is supplied by phase A and turned off when V_{inA}=80 V at the time t=3.6 ms. The resetting is carried out at the moment the voltage V_{inB} is zero at t=5.9 ms. The output voltage shows an overvoltage of several kilovolts at t=3.6 ms and an overcurrent with a peak value of 33 A at time =7 ms.

The arbitrary switching of a capacitive load could lead to a moment when it is turned off with a high voltage and is reset on another phase with a greatly different voltage. This leads to a high inrush current, which is a multiple of the nominal current.

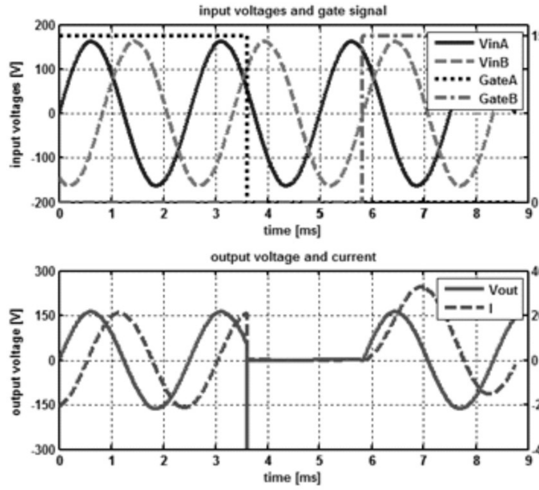

Figure 5: Worst-case switching (ohmic-inductive load)

3.2 Protection circuit of solid state switches

For switching applications in aircraft, MOSFET power switches are normally used. They have an intrinsic body diode, enabling them to only block positive voltages between their drain and source pins. Therefore, two MOSFETs can be connected in series with a common source potential so that this behaves like a bidirectional switch (Fig. 6) [15]. To deal with high currents and high voltages, such bidirectional switches are often connected in series respectively in parallel. In addition, a protection circuit has to be applied.

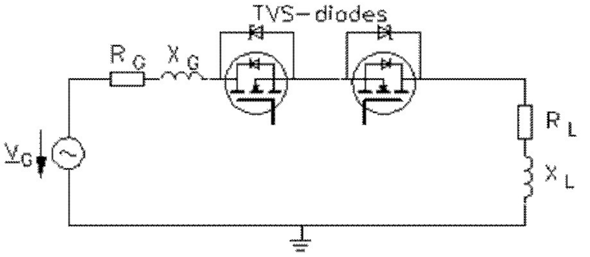

Figure 6: Protection with TVS diodes

3.2.1 Solid state power controllers

In modern aircraft, the power line to commercial loads is protected by SSPCs [5] [8]. These SSPCs use semiconductor technologies and microcontrollers. They can be remote-controlled and programmed for different trip-values. The SSPCs could be redesigned as multiplex switches for implementing phase and feeder balancing. Semiconductor devices are designed to handle currents and voltages tight to the operation values to save money and because devices with high breakdown voltages and forward current have a higher on-state voltage and a lower switching frequency. To protect semiconductor switches against overvoltages and overcurrents, protection circuitry is used. Normally, this circuit has to be designed to withstand the worst-case values. The use of switching strategies can reduce the protection circuitry that is needed. Also, the size of the cooling unit can be decreased.

3.2.2 Protection against overvoltages

The easiest way to protect the switch against overvoltage is to connect a TVS or a Zener diode parallel to the switch (see Fig. 6). TVS operates in a manner similar to Zener diodes, but are especially designed to be fast. If the voltage in operation is higher than the permitted voltage, the diode becomes conductive and reduces the overvoltage. In Fig. 7 (right), it can be seen that a gate side protection circuit named active clamping is applied. In case illegal overvoltage occurs, the Zener diode gets conductive and the MOSFET is switched on to reduce the overvoltage. Another possible way of ensuring protection is to implement a snubber circuit with ohmic and capacitive resistance, as shown in Fig. 7 (left). Overvoltages during the switching process charge the capacitor and are reduced.

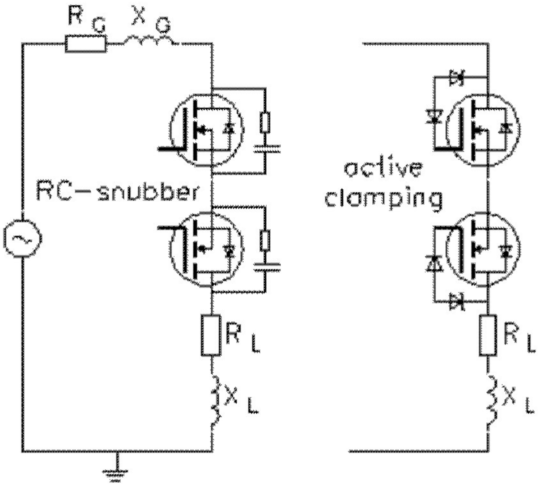

Figure 7: Protection with RC snubber (left) and active clamping (right)

3.2.3 Protection against overcurrents

Overcurrents can occur on board aircraft if a high capacitive load is switched on. If the overcurrent is at the level of the fault current, the installed MOSFETs have to be protected. Although MOSFETs are known as short-circuit-proof solid state devices, they have to be switched off as fast as possible in case a fault occurs [9].

In practice, the fault current is detected by current sensors, such as instrument shunts or current transformers, and results in a switch-off signal, which is rapidly transmitted to the driver unit of the MOSFET. This method is called the direct protection method because the overcurrent is measured directly by the use of current sensors implemented in the source path of the MOSFET. Another method, called the indirect method, observes the drain-source voltage of the MOSFET while it is switched on. If the measured voltage exceeds a permitted level, a signal for switching it off is sent to the driver of the MOSFET. The fault current should be eliminated within 10 μs in order to ensure that the MOSFET is not destroyed [10].

All the protection options have in common the fact that they need additional passive electrical elements, which result in higher cost and increased weight for the aircraft. With a better understanding of the switching process and the resulting switching strategies, both the cost and weight factor can be considerably reduced. In the following section, new switching strategies and control algorithms of the MOSFET-gate have been introduced.

3.2.4 Considerations of power quality

For aircraft applications, high power quality requirements have to be fulfilled by electrical equipment. [11] specifies the requirements and test procedures for the electrical characteristics of the Airbus A350 AC and DC equipment. The stated balancing concepts with active load switching may lead to additional system perturbations, depending on the load type and the switching rate. For 115/230 VAC equipment, different requirements are defined in [11] for steady-state and transient characteristics. Because of the stated switching strategies for different load types, additional system perturbations, caused by transients during the load switching, such as voltage spikes and voltage harmonic distortion, are kept low and should not exceed the limits defined in [11]. However, depending on the switching rate as well as the amount and power of the switched loads, the balancing concepts may affect the power quality due to modulation of voltage. In order to keep this effect low, the maximum permitted switching rate of the balancing concepts should not be higher than 25 Hz (40 ms) [12].

3.3 New switching strategies

In order to produce as few overvoltages and overcurrents as possible as a result of switching, different algorithms can be used, which act on the gate driver of the MOSFETs [13]. To illustrate the effects, the types of load have a power factor of 0.2 and a phase shift of 78.47°. The steady-state current through the load is 15 A.

3.3.1 Zero-switching strategy

SSPCs can be designed in such a way that they can measure the input voltage, the output voltage and the current [14]. A possible strategy, which is often used, is to turn on the switch when the input voltage is zero and to turn it off when the current is zero. This procedure is referred to as the Zero-switching strategy. For this strategy, no output-voltage sensor is needed. If the SSPC receives a signal to switch a load to another feeder, it waits until the next zero-point of the current is reached and switches it off at that moment. The load is connected to a different feeder at the moment when the new feeder voltage is zero. In case the load is a discharged capacitor, the inrush current will be zero because the voltage difference would be lacking. If the load is inductive, an overcurrent occurs (Fig. 5). Because the inductive loads are turned on in the voltage zero-point, the highest DC component of the current is produced. It is ensured that no overvoltages appear when it is turned off in case the load is inductive. In case the load is highly capacitive, the capacitor will be loaded to a voltage level different from zero. If this occurs and the capacitor does not unload itself fast enough while switching over to another phase, when it is turned on during the voltage zero point, it leads to a high inrush current. Fig. 8 shows the operation chart of this strategy.

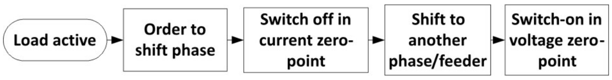

Figure 8: Zero-switching strategy

Fig. 9 shows a high inrush current because of the fact that the ohmic-capacitive load was disconnected from phase A at a high voltage and reconnected to phase B when the voltage V_{inB} is zero. With high capacitive loads, the switching off at the current zero-point leads to a maximal loading of the capacitor and leads to high inrush currents. At high power factors greater than 0.9, the negative effects are repressed through the ohmic parts.

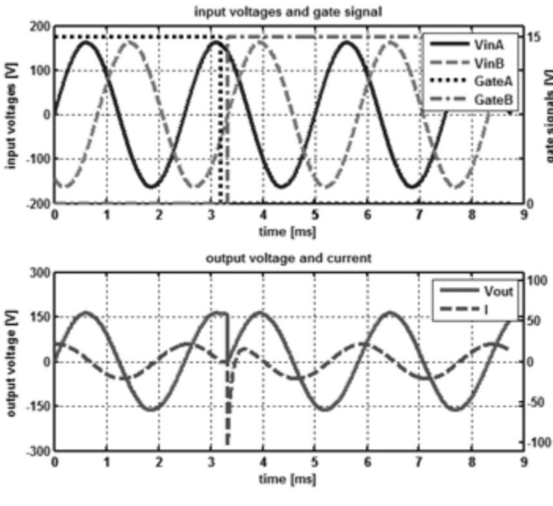

Figure 9: Zero-switching strategy at ohmic-capacitive loads

3.3.2 Vout-switching strategy

To avoid the disadvantage caused by the high capacitive turn-on current, the moment when it is turned on can be executed when the input voltage is equal to the output voltage. Thus, the voltage difference between the input and output sites of the SSPC is zero. Therefore, the output voltage has to be tracked by the SSPC. Since not just the zero-point has to be detected but the exact output voltage has to be measured as well, the requirements from the voltage sensors are higher. This procedure is referred to as the Vout-switching strategy. Even if the capacitor is being discharged during the time when the switch-over occurs, the inrush current will still be zero. With this strategy, the overvoltages that are produced by inductors when they are turned off and the overcurrents produced by capacitors when they are turned on can be avoided. But overcurrents similar to the Zero-switching strategy can appear when ohmic-inductive loads are switched. Fig. 10 illustrates the operation chart of this strategy.

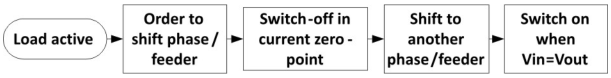

Figure 10: Vout-switching strategy

With ohmic-inductive loads, the behaviour and simulation results of the Vout-switching strategy are the same as for the Zero-switching strategy. Fig. 11 shows the

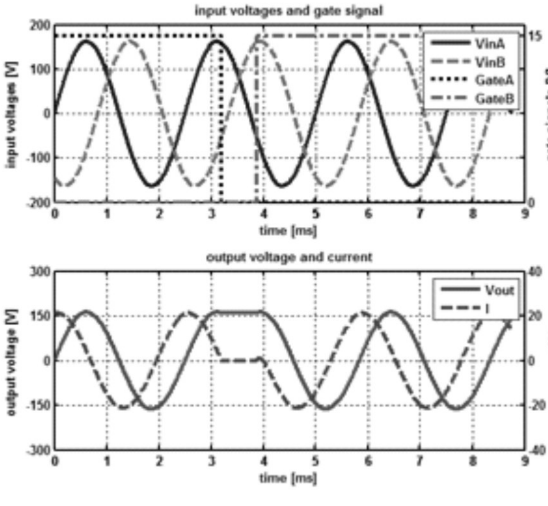

Figure 11: Vout-switching strategy at ohmic-capacitive loads

simulation results with the Vout-switching strategy at capacitive loads.

3.3.3 Phi-switching strategy

Because different strategies are optimal for different kind of loads, one way could be to determine if the load is inductive or capacitive and adapt the switching strategy. Therefore, the current and the input and output voltages have to be tracked, to determine the phase shift. This allows different switching strategies for different load types. The phase shift can be determined using a microcontroller. Because the phase shift is used, this procedure is referred to as the Phi-switching strategy. The Phi-switching strategy is illustrated in Fig. 12.

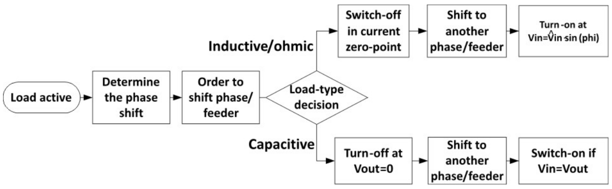

Figure 12: Phi-switching strategy

It is assumed that the load is activated and the stationary current is measured. Depending on the kind of load—whether it is inductive or capacitive—different strategies are used. If the load is inductive, the current will lag behind the voltage and the turn-off will occur at the zero point of the current to prevent high overvoltages. The turn-on on a different phase respectively feeder is executed when the input voltage is:

$$V_{in} = \hat{V}_{in} \cdot \sin(\varphi)$$

This avoids the DC part in the current and immediately leads to the stationary current without an overcurrent. In a built multiplex-switch prototype the phase shift was not determined; instead the voltage of the input is tracked and saved in the moment the current equals zero. This voltage equals $\hat{V}_{in} \cdot \sin(\varphi)$.

At ohmic-capacitive load behaviour, it is turned off at the voltage zero-point and turned on when the input voltage equals the output voltage. In most cases, this will occur at zero voltage. But because the construction of the loads is not known, other cases are possible.

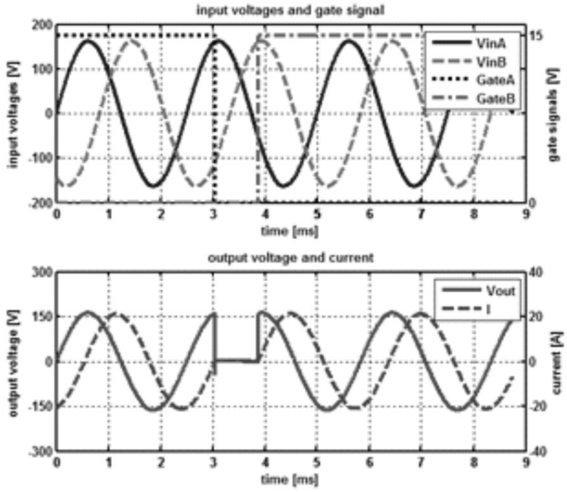

Figure 13: Phi-switching strategy at ohmic-inductive loads

Fig. 13 illustrates the simulation result using the Phi-switching strategy with an ohmic-inductive load. It can be seen that the load is turned off in the current zero point, after 1 ms the voltage of phase B equals $\hat{V}_{in} \cdot \sin(\varphi)$ and the load is activated, leading to an immediately stationary current without an overcurrent. All negative effects can be minimized with this strategy. Loads with rectifier or power factor correction (PFC) prevent that loads are feeding into the grid. Behind the rectifier is a capacitor to stabilize the voltage, meaning the output voltage meter of the solid-state power controller cannot detect a zero-crossing of the voltage. Therefore, the phi-switching strategy has to be adapted: if the microcontroller of the SSPC does not detected of zero-crossing of the output voltage within one period, the SSPC is turned off immediately independent of the actual current or input voltage.

3.4 Results

Aircraft manufacturers prescribe that loads have to follow certain specifications, such as the high of the inrush current and the maximum allowed phase shift of inductive and capacitive loads, depending on the power consumption. That includes the claim to withstand time periods of several milliseconds without energy supply. To protect the solid state power controllers, snubber circuits are used. Other papers like [4] suggest using the semiconductor switch in linear mode when it is turned on while switching high capacitive loads. Therefore, the maximum capacitance has to be calculated to ensure the transistor stays in its safe operating area (SOA). The data of the SOA is deposited in a look-up table in the microcontroller of the SSPC. The gate voltage is controlled by the microcontroller for controlling the slope of the current. During this time, the losses over the MOSFET increase. In contrast to this strategy, all the switching strategies presented in this paper ensure that the MOSFETs operate in switching mode.

The inductance of the generator is not determinative, since in aircraft hundreds of loads are connected to the generators through several busbars which have two or three branches. That is why the type of load is the most important factor for the switch-over strategy. The

Table 2: Characteristics of the different switching strategies

	Without switching strategy	Zero-switching strategy	Vout-switching strategy	Phi-switching strategy
Turn-on moment	arbitrary	Vin=0 V	Vin=Vout	$\varphi \geq 0:\ V_{in} = \hat{v} \cdot \sin(\varphi)$ $\varphi \langle 0:\ V_{in} = V_{out}$
Turn-off moment	arbitrary	I=0 A	I=0 A	$\varphi \geq 0:\ I = 0 \cdot A$ $\varphi \langle 0:\ V_{in} = 0$
Overvoltage at turn-off by ohmic-inductive loads	Yes	No	No	No
Overcurrent at turn-on by ohmic-capacitive loads	Yes	Yes	No	No
Overcurrent at turn-on by ohmic-inductive loads	Yes	Yes	Yes	No

way suggested here for reducing transition effects is to control the switching moments. Without a switching strategy, the turn-on and turn-off moments are arbitrary. The time the load is not supplied can be minimized, since only a short dead-time has to be included to ensure the former conducting MOSFET is turned off completely. The Zero-switching strategy prevents high overvoltages when inductive loads are switched off. The Vout-switching strategy also avoids high inrush current when capacitive loads are turned on. Therefore, an additional output voltage sensor is necessary. The Phi-switching strategy claims the highest demands on accuracy of the voltage and current sensing. Table 1 summarizes the characteristics and the effects of the different switching strategies. Simulation with parallel loads and models of real loads gives similar results. With parallel ohmic-capacitive loads, depending on their time constant, the absolute value of the load voltage decreases during the changeover time. This reduces the inrush current for the Zero-switching strategy. Since the output voltage is tracked by the Vout-switching strategy, the results stay the same. The Phi-switching strategy in this case cannot prevent the overcurrent when it is turned on at ohmic-inductive loads.

Switching operations should be minimized to ensure that the DC current components are decayed in order not to perpetuate them. For aircraft using phase and feeder balancing in the future, it is recommended that the Phi-switching strategy is used.

4 Conclusion

The two methods introduced—phase and feeder balancing—aim at optimizing the distribution networks in aircraft by the use of intelligent switching nodes. Phase balancing minimizes the return current leading to a smaller ESN in future CFRP-aircraft. Feeder balancing uses the non-concurrence of the feeder load to symmetrise the feeders which makes it possible to reduce the power feeder diameters. The intelligent switching nodes using the two methods contain modern power semiconductors, such as MOSFETs, to execute the switching operations.

When the switching operations increase, the implemented power semiconductor switches are extremely stressed by negative switching effects like overvoltages and overcurrents. In order to reduce these negative effects, different switching strategies have been presented. Because of the simulation result, it is recommended to use the Phi-switching strategy. In general, to protect the switches from overvoltages, TVS diodes, RC snubbers or active clamping can be used. For protection from overcurrent, the direct method observing the current or the indirect method observing the drain source voltage can be adopted. Together with the proposed switching strategies, the protection circuit can be designed to be smaller and leads to a lighter implementation of the intelligent switching nodes in modern aircraft.

The analytical examinations as well as the simulations are based on the assumption of ideal devices. Effects such as saturation of iron cores of transformers are not considered. To test and evaluate the feasibility of the different switching strategies, a multiply switch has been built. The experimental results show the feasibility of the different strategies.

In modern aircraft, the power factor is limited and depends on the load power. The higher the load power consumption, the higher the power factor. This reduces the need for a switching strategy because the negative effects are low. However, some loads which do not fulfil these requirements can still be integrated into the aircraft. On the other hand, the switching strategy could lead to more generous power factor limits. By using an intelligent switching strategy instead of switching arbitrarily, it leads to a smaller layout of the semiconductor and snubber circuits.

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