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Generic functional modelling of multi-pulse auto-transformer rectifier units for more-electric aircraft applications

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Abstract The Auto-Transformer Rectifier Unit (ATRU) is one preferred solution for high-power AC/DC power conversion in aircraft. This is mainly due to its simple structure, high reliability and reduced kVA ratings. Indeed, the ATRU has become a preferred AC/DC solution to supply power to the electric environment control system on-board future aircraft. In this paper, a general modelling method for ATRUs is introduced. The developed model is based on the fact that the DC voltage and current are strongly related to the voltage and current vectors at the AC terminals of ATRUs. In this paper, we carry on our research in modelling symmetric 18-pulse ATRUs and develop a generic modelling technique. The developed generic model can study not only symmetric but also asymmetric ATRUs. An 18-pulse asymmetric ATRU is used to demonstrate the accuracy and efficiency of the developed model by comparing with corresponding detailed switching SABER models provided by our industrial partner. The functional models also allow accelerated and accurate simulations and thus enable whole-scale more-electric aircraft electrical power system studies in the future.

1. Introduction

Driven by the demand to optimize aircraft performance, decrease operation and maintenance costs and reduce noise pollution, the aircraft industry has been pushed towards the concept of the More-Electric Aircraft (MEA). In the MEA, many functions which are conventionally managed by hydraulic, pneumatic and mechanical power, will be replaced with devices driven by electrical power.[1,2] Such replacement would

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reduce system weight and volume, increase overall reliability, capability and maintainability, and provide higher durability for aircraft operations.[3] Aircraft power electronics have also been affected by this trend. The need for power conversion and driving equipment on-board has become significant. Recently, the usage of AC-DC conversion has become a common feature for aircraft power distribution systems. In general, there are two main types of this AC-DC power conversion: the PWM active front-ends and passive multi-phase transformer rectifiers. The former has seen increased application incorporation such as electromagnetic actuators[4] and electrical starter-generator applications.[5] However, the latter seems to be the main power source for high-power DC load such as aircraft Environment Control Systems (ECS) due to its simple structure and high reliability. The civil aircraft has long been using Transformer Rectifier Unit (TRU) to produce 28 VDC from 115 V, 400 Hz ACsources. However, recently the auto-transformer rectifier has received more attention in aerospace industry due to its reduced kVA rating compared with TRUs.[6]

A number of possible ATRU topologies have been proposed during the last decade.[7–13] These ATRUs can be categorized into 12-pulse types, 18-pulse types, 24-pulse types, etc., according to the number of pulses in the rectified voltage or in the line current during one fundamental cycle. Among these topologies, the 18-pulse ATRU seems to be a preferable option. This is due to the fact that it has higher power quality than the 12-pulse type and less devices than the 24-pulse or other higher pulse type ATRUs. The 18-pulse ATRU is now actually being used on-board B787, the Dreamliner, supplying power to the environment control system.[14]

The 18-pulse ATRUs can be divided into symmetric and asymmetric types depending on the symmetry of voltages on the secondary side of the transformer. For symmetric 18-pulse ATRUs, the voltages on the secondary side of the auto-transformer are with the same magnitude (normally the same with the magnitude of voltage on the primary side) and have an equal phase shift of 40° from each other. The load power is equally shared by the three directly-connected diode bridges. For asymmetric 18-pulse ATRUs, however, the voltages on the secondary side are of different magnitudes. The voltage phase-shift angle is also not necessarily 40°.

The increased power electronics and motor drives on-board MEA are bringing significant modelling challenges due to its wide variation in time constant. The challenge is to balance the simulation speed against the model accuracy and this is dependent on the modelling task. Four different modelling layers are defined according to the modelling bandwidth, i.e. architectural models, functional models, behavioural models and component models[15,16] as shown in Fig. 1.

The architectural layer computes steady-state power flow and is used for weight, cost and cabling studies. In the functional level, the system components are modelled to handle the main system dynamics up to 150 Hz. The error of models in this level should be less than 5% in respect of the behavioural model accuracy. The behavioural model uses lumped-parameter subsystem models and the modelling frequencies can be up to hundreds of kHz. The component models cover high frequencies, electromagnetic field and ElectroMagnetic Compatibility (EMC) behaviour, and perhaps thermal and mechanical stressing. The bandwidth of component models can be up to MHz region if required.[16]

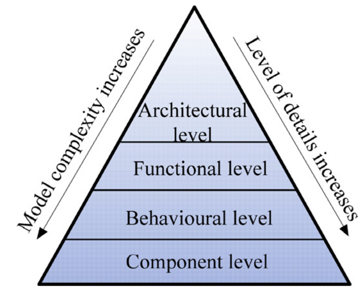

Fig. 1 Multi-level modelling paradigm.16

This paper aims to develop a general functional model of ATRUs which allows future engineers to study ATRUs in a more efficient and effective way. The functional models allow accelerated and accurate simulations and thus enable a whole-scale MEA Electrical Power System (EPS) studies in the future. The developed ATRU model is based on the vector concept and in the synchronous dq frame. This method has been widely used in modelling electrical machines.[16–18]

The remainder of the paper is organized as follows: Section 2 briefly outlines the operation of ATRUs; Section 3 gives details of the development of the proposed modelling technique; an 18-pule ATRU is used for the effectiveness and efficiency studies in Section 4; Section 5 draws the conclusions of the paper.

2. Operation principles

The design of multiphase transformer rectifiers has been well discussed in Ref. 19. The auto-transformer rectifiers normally comprise a phase-shift transformer and a set of three-phase diode bridges as shown in Fig. 2. The phase shift transformer is not necessarily an auto-transformer type. However, the auto-transformer is a preferred option due to its low kVA ratings. In this paper, we mainly focus on auto-transformer rectifier units.

As can be observed in Fig. 2, the auto-transformer is used to create three sets of three-phase voltages on the secondary side, i.e. (v_{a1}, v_{b1}, v_{c1}), (v_{a2}, v_{b2}, v_{c2}) and (v_{a3}, v_{b3}, v_{c3}). These resultant 9 phases are then fed into three diode bridges supplying power to the dc link. At each instant of time, there are two diodes conducting. These two conducting diodes allow the largest line-to-line voltage to be applied to the DC side. We refer to the ATRU system shown in Fig. 2 as a "3-9-DC" system. For some ATRUs, especially asymmetric ones, the voltage sources on the primary side of the transformer also feed

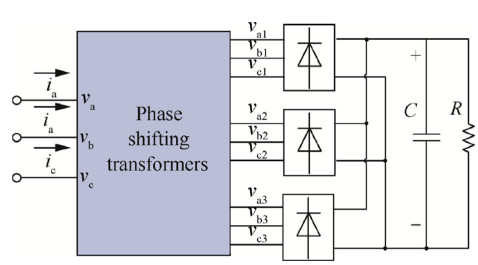

Fig. 2 General auto-transformer rectifier units.