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Behavioral Modeling Paradigm for More Electric Aircraft Power Electronic Converters

Husan Ali

Abstract

To control the power flow among various energy sources and loads of a power system of modern more electric aircrafts, power electronics converters are employed. The integration of multiple sources into distribution system and their interconnection with variety of loads through power electronic converters results in a complex dynamic system. Modeling of these systems prior to implementation becomes necessary to analyze and predict system's behavior. The classical modeling approaches require detail knowledge about the topology and parameters of the active and passive components of the power electronics converters. While in modern system, most of the power electronics converters are ready to use power electronics modules. These modules come from different manufacturers, lacking the necessary information to build the conventional switch or average models. The chapter would cover dynamic behavioral modeling technique for power electronics systems to be employed in more electric aircrafts, which do not require any prior information about the internal details of the system.

Keywords: behavioral modeling, two port network, power electronic converters, system identification, more electric aircraft

1. Introduction

The ever increasing consumption and growing demand for reliable supply of electrical energy has led the electrical engineers to do more research in the field of distributed energy systems (DES). A distributed energy system delivers power to different electrical and electronic loads, by conventional as well as number of renewable energy sources, e.g. solar energy, wind energy, bio mass, fuel cells etc. With the availability of these resources comes the issue of their integration into existing power distribution system. Thanks to the advancement in power electronics technology, which has enabled the power distribution systems to supply various loads not only from the traditional utility grid but also from modern alternative energy sources. The recent trend of shift in power distribution systems from centralized architecture to distributed architecture has led to a significant increase in the number of power electronics converters being employed in these power distribution systems. The conventional power systems based upon a centralized architecture have only a single source delivering power to various loads [1–3].

The conventional power systems are being replaced with more advanced distributed energy systems for various applications, in which loads are supplied by multiple energy sources through a number of power electronics converters, distributed throughout the system [4–10]. These hybrid energy systems include more than one source of energy, energy storage elements and active and passive loads, either dc, ac or both. This implies the use of power electronics converters, to control the power flow over the entire system, hence also called electronic power distribution system (EPDS). It illustrates that in future EPDS the dynamics of electrical energy generation, distribution and consumption will be dynamically decoupled through the use of power electronics converters. In the literature, the distributed energy systems have been discussed for most of the modern state of the art applications, i.e. more electric aircrafts (MEA) [11], more electric vehicles (MEV)/hybrid more electric vehicles (HMEV) [12], all electric ships (AES) [13], telecommunication systems and data communication systems [3, 14], and for commercial and residential systems [15, 16].

The integration of multiple sources into distributed energy system and their interconnection with variety of loads through power electronics converters in more electric aircrafts results in a complex dynamic system [17]. Therefore, it becomes necessary to model these systems prior to implementation for analysis and prediction of system's behavior [4, 13, 18–21]. The requirement to model power converters for system level analysis was first discussed in [18], and subsequent work has been done in this direction in [4, 13, 19]. However, the pre-requisite for all of the classical modeling approaches regarding the analysis of the overall system is to have complete knowledge about the topology and parameters of the power electronics converters and other subsystems employed [20–23]. In more electric aircrafts, most of the power electronics converters used are ready to use power electronics modules. The issue commonly faced is that, different modules such as converters, filters and loads are designed by different vendors and lack the necessary information required to build the conventional switch or average models. **Figure 1** shows a commercial dc-dc converter [24] which serves as a ready to be employed power electronics module.

This leads us to the behavioral or black-box modeling approach, which does not require any prior information about the topology and parameters of the system and hence is very effective for modeling different power electronics converters based systems. The behavioral modeling concept is based upon the measurement of a set of g -parameters, which are obtained via performing certain measurements at only the input-output terminals of the converter. The dynamic behavioral models developed using this approach are able to predict the transient as well as steady state behavior of the system.



Figure 1.
Commercial dc-dc power electronics converter module.

2. Overview of power distribution systems

In the literature, two most popular power distribution approaches have been centralized approach and distributed approach. A brief overview is given here.

2.1 Centralized power architecture

The conventional power systems are mostly based upon a centralized architecture. The centralized power systems have only a single power electronics converter delivering power to various loads. **Figure 2** shows the conventional centralized power distribution architecture for a typical telecommunication system. The -48 V bus is supplied by the ac-dc converter and battery storage is used as back up. In this case a single dc-dc converter delivers power to several loads through various output busses.

The biggest drawback of such centralized power systems is that they lack reliability, i.e. in case the single intermediate converter fails, the whole system will shut down.

2.2 Distributed power architecture

In distributed energy systems, loads are supplied by a number of different power converters which are distributed throughout the system. In contrast to centralized power architecture the distributed power architecture offers several advantages. The distributed power system (DPS) offers improved reliability in terms that if one of the converter fails, the whole system will not shut down. The parallel connected converters on the load side provide the option of immediate replacement of any damaged module, while keeping the rest of the system operational.

The aircraft power systems are also undergoing a great change by moving towards more electric aircraft, adopting distributed architecture. The conventional power sources such as pneumatic, hydraulic and mechanical are being replaced with electrical power. The MEA concept promises to improve the reliability and efficiency of the overall system and at the same time reducing the weight and size of the equipment [11, 12, 25].

The researchers have come up with various proposals for MEA technology implementation. One of the proposal is based upon variable frequency 230 V_{AC} bus as shown in **Figure 3** [26]. The traditional constant frequency generator is being replaced with variable frequency generator. The auto transformer rectifier unit (ATRU) and pulse width modulation (PWM) rectifier are in cascade with inverters to feed the motors. Single phase ac loads are connected to the bus through power factor correction (PFC) circuits. The 28 V_{DC} bus is connected to the variable frequency ac bus through transformer rectifier unit (TRU) and dc-dc converter, which are then connected to a backup dc voltage source and various dc loads.

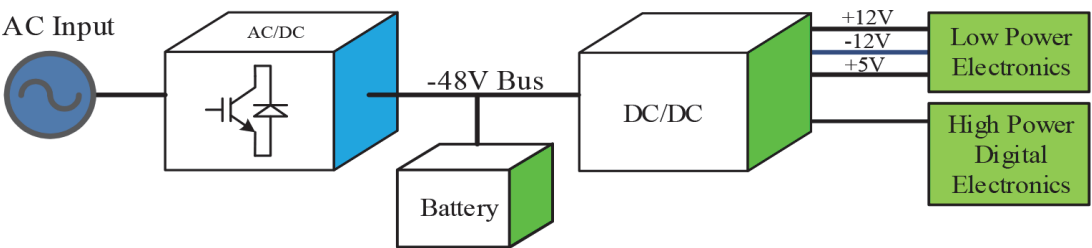


Figure 2.
Conventional centralized power architecture for telecommunication system [3].

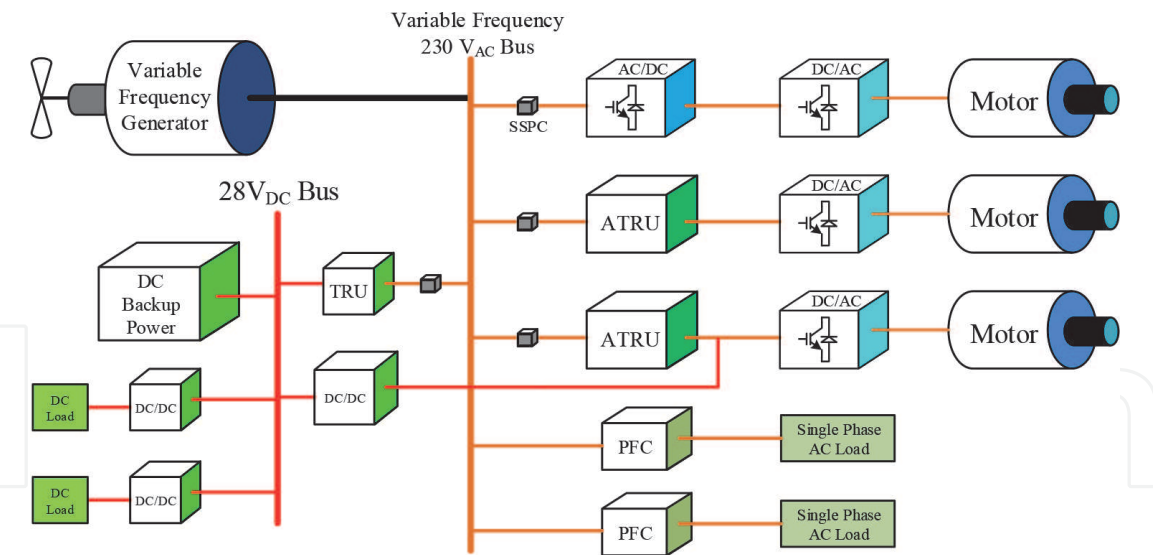


Figure 3.
Distributed power system for MEA using variable frequency ac bus.

As can be seen from above example, there is a shift in power distribution system architecture for more electric aircrafts. In an overall complex network the traditional utility network along with renewable energy sources and storage elements is connected to multiple loads through power electronics converters. The power electronics converters involved are ac-dc, ac-ac, dc-ac and dc-dc. Also these converters can be either unidirectional or bidirectional and have connection configuration of series or parallel, mainly depending upon the application. Therefore, it is required to build models for these power electronics converters which have become a key part of the modern DES for more electric aircrafts.

3. Modeling hierarchy review

As per the above discussion, to simulate and analyze the behavior of a complete system, it is required to develop models for different subsystems. In the literature, modeling of power electronics converters from detailed switching models to very abstract behavioral models has been discussed. A brief review is given here.

3.1 White box models

When all the necessary data to model the system's behavior is available, then in such cases a white-box modeling approach is useful. The switch and average models are types of white-box modeling approach [27, 28]. At converter level, the switch models are the most detailed ones which give the designer an idea about workflow of the circuit during various switching states [29]. These are also used to study and model electromagnetic interference (EMI) phenomenon [30]. Similarly, the simplified average models can represent the behavior of the system with certain assumptions. The large signal averaged models can be used to simulate and analyze stability of power electronics converter systems. The average models are linearized around a particular operating point to obtain linear time invariant (LTI) model.

Middlebrook presented the concept of state space average models for power electronics converters [31]. In this approach the duty cycle of the converter is averaged over one complete period. The average modeling results in a continuous model that ignores the switching action but includes the nonlinear behavior of the

converter. In order to apply linear system theory techniques, the average model is linearized around an operating point. The operating point is then used to design the controller for the system and analyze stability of the system. Often the parasitic elements are neglected to simplify the modeling process. Yet the average models provide a good solution for modeling and analysis of the converter. The general form of state space average model for a pulse width modulation (PWM) converter is as given in Eq. (1)

$$\begin{aligned}\dot{x} &= \sum_{i=1}^n (A_i d_i x + B_i d_i u) \\ y &= (Cx + Du)\end{aligned}\quad (1)$$

where x , u and y represent the state, input and output variables respectively, d_i is the duty cycle, and A, B, C, D are system matrices.

Few other modeling techniques in this category are; generalized state space average models [32], discrete average models [33] and cyclic average models [34]. However, state space averaging is most widely used due to its simplicity and good dynamic estimation for most applications.

The averaging techniques have also been applied to three phase ac systems, i.e. ac-ac, ac-dc and dc-ac PWM converters [35]. The average models for three phase systems are transformed to synchronous dq reference frame, in which the system is operated at a certain point for the application of small signal modeling techniques. The average modeling of three phase diode and line commutated rectifiers has also been widely investigated [36, 37].

Both in the case of switch as well as average models, the designer has complete information about the topology and parameters of the converter. But the white-box modeling approach fails in case of power electronics modules where the designers do not have any or complete information to build switch or average models.

3.2 Gray box models

Depending upon the system and the information about it, it is possible to approximately write state space equations with unknown parameters which are to be estimated later, this method is called gray box modeling [38]. It is an intermediate case falling between white-box and black-box modeling, where part of the information is available to the designer from the datasheets about the converter topology and internal circuit parameters. Hence part of the model reflects the design of the system while remaining which is numerically modeled serves as black-box. Some reduced order average models also fall within this category.

3.3 Behavioral or black-box models

Behavioral models are mainly not concerned with the detailed internal structure or parameters of the converters. These models are built without requiring any prior information about the internal parameters of the converter and also called black-box models [39, 40]. The term *behavioral modeling* is normally associated with the modeling of such type of converters. It refers to the modeling technique in which models for power electronics converters and passive modules e.g. electromagnetic induction filters are built without any available information about their internal design and components. The models of power electronics converters with minimum or no detail about the system are used to analyze the input-output behavior of the system.

The behavioral modeling of power electronics converters can be broadly classified into linear and non-linear techniques, depending upon the model structure. These techniques are oriented to either converter or system level design and based upon parametric and nonparametric identification methods. The parametric methods describe the system's behavior using transfer function or state space models. These models are identified using either time or frequency domain data. The non-parametric methods describe the system's behavior using impulse response or frequency response data. Also, a non-parametric model can also be used as input for parametric identification such as, frequency response data can be used to identify a transfer function model.

3.3.1 Linear techniques

The very first linear black-box modeling techniques were used to obtain the model of the plant, i.e. from the duty cycle to output voltage response of the converter. The model was then used to design controller for the system. Middlebrook presented the method to experimentally measure the loop gain frequency response through ac sweep signal, which results in a non-parametric black-box model [41]. Later, further work has been done to determine the control to output response of switching converters using either parametric or non-parametric methods. The parametric method is used in [42] to identify coefficients of a discrete difference equation using a pseudo random binary signal (PRBS) as excitation input signal. A non-parametric method is used to identify the frequency response of a converter using impulse response in [43]. An improved nonparametric cross-correlation method of system identification is proposed in [44]. It aims to improve the accuracy of frequency response identification, especially at high frequencies near the optimum closed loop bandwidth frequency. Fourier analysis is applied to the identified impulse response to obtain the small signal frequency response. Linear black-box models have also been used to synthesize controllers for power converters, for which it is difficult to obtain analytical models, i.e. series resonant converter [45].

The system oriented linear behavioral modeling technique has been employed to model components of power system as an input-output network in [46]. The sub-systems are modeled as two port linear network using small signal linear average approach. The g -parameters as transfer functions are obtained by averaging state-space equations followed by small signal perturbations. Another method to obtain the g -parameters is by input-output frequency response measurements followed by parametric identification algorithm.

3.3.2 Non-linear techniques

Most of the power electronics converters are non-linear systems, so the linear techniques are valid only around a particular operating point. The non-linear modeling techniques have been developed to obtain models which are valid for a wide operating range. In order to model the duty cycle to output voltage response for a dc-dc converter, a non-linear autoregressive moving average with exogenous input (NARMAX) model is employed in [47], which consists of a non-linear discrete differential equation. It requires time domain data to identify the model, which is obtained by perturbing the duty cycle and measuring the output voltage. Neural networks have the ability to model non-linear functions which can be related by input-output data for a non-linear system. A neural network is applied to model the control to output voltage behavior of a converter for control design in [48].

Another technique which can be employed when some limited information is available is called, Wiener and Hammerstein approach [49, 50]. These models are valid when the non-linearities are present in the steady state variables only, in case the dynamic part of the system is also affected by non-linearities then this approach fails. **Figure 4** represents Wiener and Hammerstein modeling approach. In these models, the linear block represents dynamic system as transfer function while the non-linear block represents steady state operating point. In Wiener model the linear block precedes the non-linear block and it is opposite in the case of Hammerstein model. The structure of Wiener and Hammerstein models is limited to single input and single output and it also requires time domain data to build the models.

In this dissertation lookup table and polytopic structure based non-linear behavioral modeling methodology has been described, where lookup table based approach has been used for mild non-linearities, while for severely non-linear dynamic relations more complex polytopic structure based approach has been applied.

3.4 System level Modeling

To design modern distributed energy system, which includes number of power electronics modules connected in various configurations, module based behavioral modeling is required for the analysis of the complete system. Two port network utilizing g -parameters based converter level modeling was initially applied in [51]. This method was subsequently used to analyze the interaction among subsystems in a networked system [52]. But in this approach first small signal model of the converter is required which is used to derive the g -parameters. The small signal modeling requires knowledge about the topology and parameters of the converter, which as mentioned above is often not available to the designer.

To model the large signal behavior of dc-dc converters based upon system identification, a different approach was proposed in [49]. In contrast to g -parameters based modeling, it is a circuit oriented approach which partially relies on the data provided in the datasheet. The model is a hybrid Wiener-Hammerstein structure, where the static non-linear block is identified from the data about efficiency, static regulation and thermal characteristics, while the dynamic linear block is identified from the transient response data. This technique was also used to model a nanogrid, where model for each subsystem is divided into two blocks [53].

Modern distributed energy systems are based upon commercial converters [54–56], with lack of information to build conventional white box models.

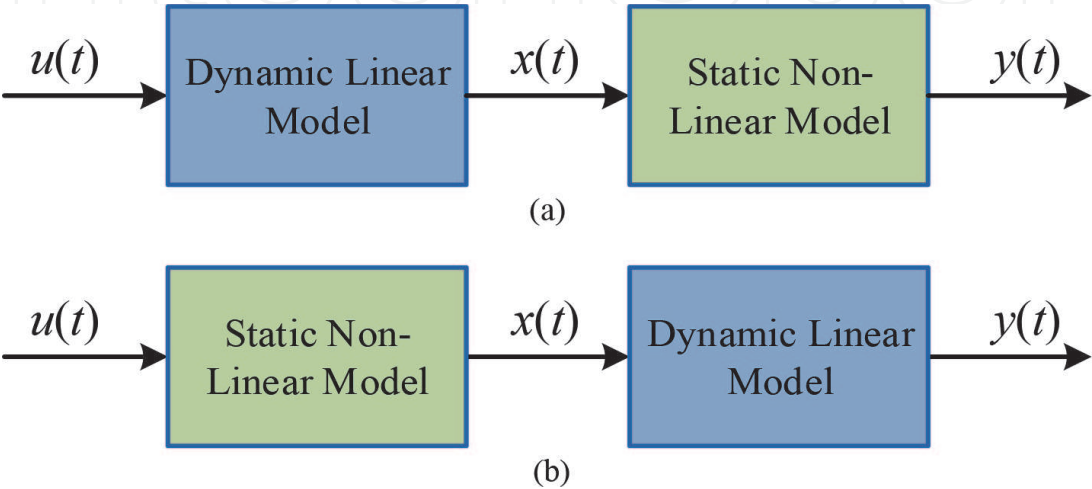


Figure 4.
(a) Wiener and (b) Hammerstein model structures.

Therefore, among various techniques mentioned above g -parameters based behavioral modeling would be most effective [57]. The main advantage of g -parameters based behavioral modeling methodology is that large system can be subdivided into subsystems, then these can be easily combined after modeling resulting in any desired architecture. In order to model each subsystem, the idea is to obtain the parameters that characterize their dynamic behavior of each via accessing only the input–output terminals [58].

4. Current lack in state of the art

To integrate several different power electronics converters as part of electronic power distribution system, it is often required to model in priori and simulate the whole system [4, 13, 18, 20]. It can speed up the design process and reduce the amount of experimental work. Hence, behavioral modeling approach should be adopted to model such converters. There are certain challenges faced during this process which are summarized below:

One problem which arises during behavioral modeling is the high order of the measured g -parameters. The individual models of the converters should be low order and represent only the input–output dynamics, i.e. behavior of the system. So certain technique should be adopted that the behavioral model is not only successfully able to represent the behavior of the system but also is computationally efficient to consume less simulation time.

The behavioral models should cover the entire operating range of the system and predict the dynamic response of the system under small or large signal disturbances either at source or load. But power electronics converters due to their switching action are inherently non-linear systems and behavioral models developed at one operating point are not valid over the wide operating range. Hence non-linear behavioral modeling approach is required to be adopted for such systems, which will enable these models to analyze and predict the response of the system over the entire operating range.

5. Behavioral modeling methodology

This section presents the methodology to build the behavioral models for power electronics converter based systems. In this methodology the dynamic behavioral models are developed to analyze and predict the behavior of power electronics converters based systems. The data required to build behavioral models is obtained via measurements at the input–output terminals. These measurements followed by identification and order reduction steps result in certain number of g -parameters which are then used to build the behavioral model.

Two different approaches are used to acquire data by performing certain measurements for the behavioral modeling of the system. One is based upon the frequency domain, the second one is based upon time domain. To acquire data using frequency response based method a network analyzer is used. It generates an AC sweep signal which introduces perturbation in the signals to be measured. Then the input and output signals to which perturbation is already being added, are given to network analyzer for frequency response measurement. To perform the measurements using transient response based method, a step change is introduced in the input signal, which results in transient change in the output signal. Then both the input and output time domain signals are recorded using an oscilloscope and subsequently used for identification of frequency response.

While the measurements are made, it is ensured that the parameters of the behavioral model completely represent the internal dynamics of the system, excluding any source or load effects. **Figure 5** shows general view of the black-box based two port network representation for the behavioral modeling of a dc-dc converter.

In **Figure 5** the symbols can be generalized as v_j and i_j representing voltage and current, where $j \in (i, o)$, the subscripts i and o represent the input and output terminals respectively.

Once the data is obtained by performing these measurements, then system identification techniques are applied using the simulation package, i.e. MATLAB/SIMULINK [59] to develop the relationship between the specific input and output for which the measurements are recorded. It should be noted that once the data is obtained using either of the two measurement techniques then the processing of data to build models does not require any other information about the converter. The parameters obtained from measurement data acquire all the information required to build behavioral model of the system.

In order to address the issue of high order modeling, Hankel singular values based order reduction technique is employed. In addition a criteria is proposed which determines the number of states required to be retained for the reduced order model. The reduced order model obtained using this approach is not only successfully able to represent the behavior of the system but also is computationally efficient and requires less simulation time.

The verification and validation methodology is used to investigate the behavioral models for power electronics converters based systems. For each case under study, the methodology is first verified via simulation. During this step a simulation model of the system is setup in certain simulation packages, i.e. MATLAB/SIMULINK or SABER [60]. In the next step validation of the system is performed for experimental setup. The experimental setup is based upon certain laboratory made prototypes or

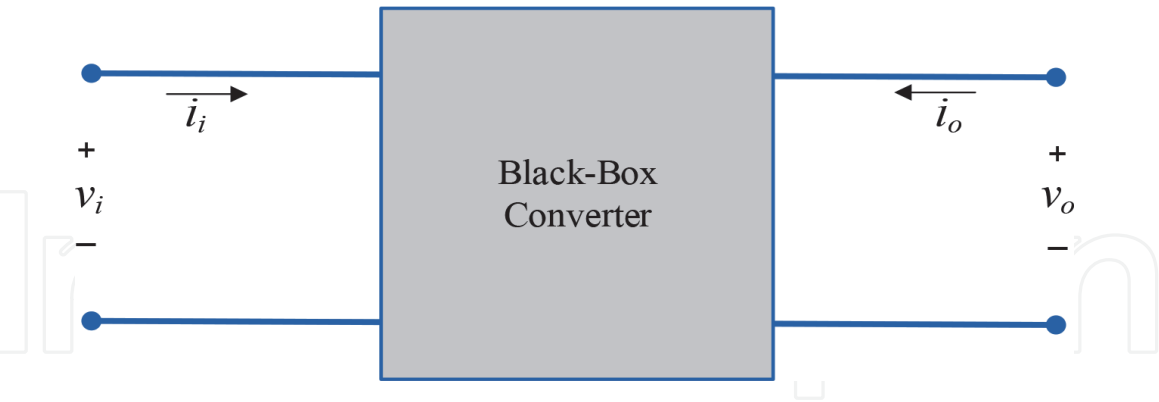


Figure 5.
Two port network based behavioral model for dc-dc converter.

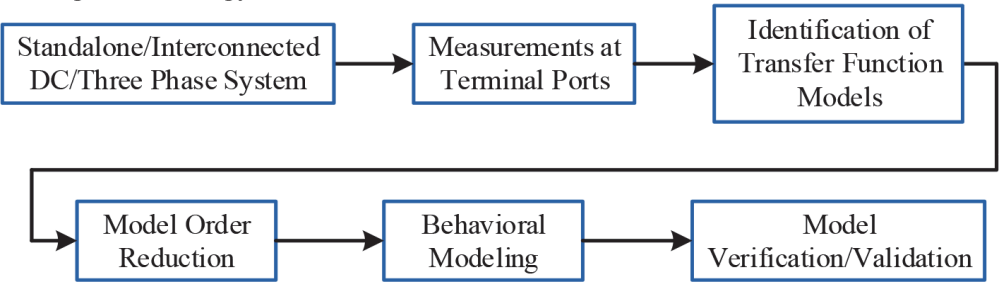


Figure 6.
General flowchart of behavioral modeling methodology.

commercial power electronics converters. The degree of matching between the results of actual system and its behavioral model is evaluated using root mean square deviation (RMSD). The two step, i.e. verification and validation based methodology serves well to authenticate the modeling procedure. **Figure 6** shows the general flowchart of behavioral modeling methodology.

6. Tow port network based behavioral modeling power electronic converters

Two port network based models have been extensively applied for the analysis of dc-dc converters [61, 62]. In the linear two port representation of dc-dc converters, the input and output port parameters constitute a set known as g -parameters. The un-terminated g -parameters represent the real internal dynamics excluding the source and load effects. The g -parameters based two port network model is used to build a small signal linear model of a dc-dc converter around a particular operating point. It is a hardware-oriented behavioral modeling approach, which does not require any prior information about either the topology or internal design of the converter. Hence there is no difference in the modeling methodology for various types of dc-dc converters, i.e., buck, boost, etc. The complete behavioral model is based upon the measurement and identification of four linear time invariant (LTI) models as transfer functions in the Laplace domain.

For the two-port network model shown in **Figure 7**, the input port is represented by a Norton equivalent circuit while the output port is represented by a Thevenin equivalent circuit [21]. It represents an un-terminated network, so the dynamic system based upon it results in a model which consists of the internal dynamics of the converter only. To achieve this the measurement setup should have minimum interaction either with the source or with the load. This is achieved when the converter is fed from a low output impedance voltage source and connected to an electronic load in constant current sink mode [63]. This setup helps in minimizing the effect of other elements such as filters and other converters upon the measurements for the system under test.

In **Figure 7** the symbols can be generalized as v_j and i_j representing voltage and current, where $j \in (i, o)$, the subscripts i and o represent the input and output terminals respectively.

The four transfer functions shown in **Figure 7**, required to build the behavioral model are;

Y_i : Input admittance.

H_i : Back current gain.

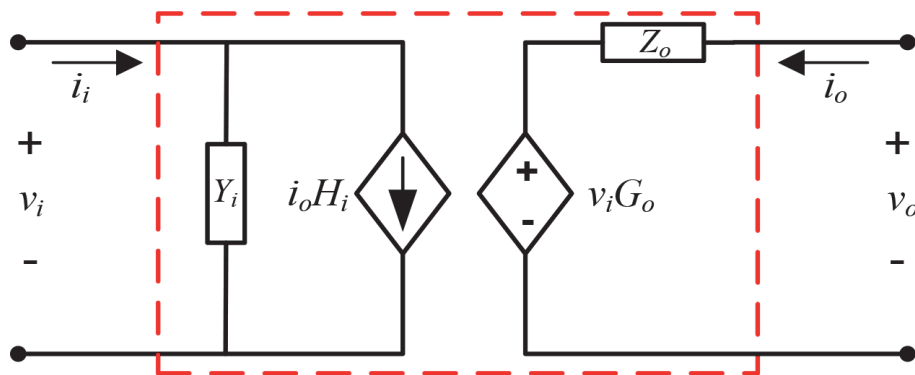


Figure 7.
G-parameters based two port network model for dc-dc converter.

G_o : Audiosusceptibility.

Z_o : Output impedance.

Mathematically the g -parameter set can be written as shown in Eq. (2)

$$\begin{aligned} Y_i = g_{11} &= \left. \frac{i_i}{v_i} \right|_{i_o=0} & H_i = g_{12} &= \left. \frac{i_i}{i_o} \right|_{v_i=0} \\ G_o = g_{21} &= \left. \frac{v_o}{v_i} \right|_{i_o=0} & Z_o = g_{22} &= \left. \frac{v_o}{i_o} \right|_{v_i=0} \end{aligned} \quad (2)$$

In **Figure 7**, the direction of i_o shown results in a positive value for Z_o . In case the direction of i_o is reversed, then ($Z_o = -v_o/i_o$) which will only result in phase shift of 180° for Z_o during the measurement.

The small signal input variables of the two port network are the input voltage and output current (v_i, i_o) while the small signal output variables are the output voltage and input current (v_o, i_i). In terms of these variables, the two port network model of **Figure 7** can be represented in matrix form as shown in Eq. (3) [18].

$$\begin{bmatrix} i_i \\ v_o \end{bmatrix} = \begin{bmatrix} Y_i & H_i \\ G_o & Z_o \end{bmatrix} \begin{bmatrix} v_i \\ i_o \end{bmatrix} \quad (3)$$

The output impedance frequency response measurement contains information regarding the response of the converter to dynamic load changes at different frequencies. The output impedance shows how a converter regulates and responds to various load changes, while the input admittance does so concerning any interaction from the source. This determines the sensitivity of a power system to input filter or input power components. The input admittance measurement gives the designer idea about the integration of a power module into another system. An audiosusceptibility frequency response measurement determines the transmission of noise from the input of the system to the output. It tells about the ability of the converter to reject noise appearing at the input.

7. Conclusion

The focus of this chapter is to present a methodology for the development of behavioral models for various power electronics systems of more electric aircrafts. The dynamic behavioral models developed are being used to simulate, analyze and predict the behavior of the systems investigated. As most of the modern power electronics modules are black-box type, so the models representing these systems should be obtained via measurements at only the input–output terminals of the system. The resulting behavioral models should represent the internal dynamics of the system and predict its transient as well as steady state behavior. Thus the proposed behavioral modeling methodology can be successfully applied to standalone power electronic converters as well as complex systems comprising of multiple sources, interface converters and loads. The model verification is done by application of certain test signals to the actual system and its behavioral models and then comparing the response of both. The close matching of results would confirm the accurate modeling.

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