Dynamic Equivalents of Active Distribution Networks: A short Review

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1 Introduction

The complexity of modern power systems, despite impressive progress in computational architectures, still necessitate simplified representation of their parts for local dynamic studies. The high penetration of Distributed Generation (DG) at the transmission and distribution network levels, the new load types and increased use of power electronics are among key factors contributing to the systems' complexity. Particularly, representation of active distribution networks (ADN) in dynamic studies became an important research and practical implementation question. This report shortly reviews previous and existing approaches for dynamic equivalencing of ADNs and offers some recommendations for future research on this important issue.

The report is organized as follows. First, the problem of dynamic equivalencing is shortly presented together with approaches to compute them. This is followed by a quick review of past notable works on this problem. Next, the approaches for dynamic equivalencing of ADNs, proposed so far in literature (available to the author), are reviewed. The reports ends with some recommendations for future research.

2 Dynamic equivalents: The problem and approaches

In forming a dynamic equivalent the whole system is divided into three subsystems:a study system or system's part of interest (internal system to be fully represented and studied), a boundary system that is retained in the system model and external system to be equivalenced. Then the problem of dynamic equivalent boils down to find a simplified and low-order representation of external system without compromising its important dynamic characteristics and behaviour as seen from the internal system.

Major approaches to power system dynamic equivalencing may be summarized as follows:

- Dynamic model reduction approach (modal, Hankel norm, Krylov, singular value decomposition),
- Coherency approach, and
- Identification approach.

Dynamic model reduction approaches apply mathematically sound approaches for model order reduction (these approaches include: Hankel norm approximation, singular value decomposition (SVD), Krylov method, etc.). In modal approach (this approach is prevailing among model reduction) a complete set of differential-algebraic equations, describing the entire system, is linearized. Then the eigenvalues and eigenvectors of linearized system are computed and analyzed. The modes which have negligible effect on the internal (study) system are eliminated.

Major steps of coherency approach include:

- Identification of coherent generation groups (usually all generators which swing together at the same frequency and at close angles are identified as one group),
- All generating units of each coherent group are connected to an equivalent bus through ideal complex ratio transformers,
- Each group is replaced by one equivalent generator by a dynamic aggregation method.

Identification approach generally involves three steps:

- The external system is represented by a hypothesized structure that is simpler than the original,
- An error function is formulated to compare the equivalent system response with the original system response,
- The parameters of hypothesized model are estimated while the error function is minimized.

Identification approaches are further divided in:

- white-box approach,
- black-box approach, and
- grey-box approach.

In white-box approach a hypothesized structure actually involves exact mathematical modelling of all physical components of the system by writing down all known relationships between relevant variables. Then the parameters of this known structure based on first principles are identified.

In black-box modelling, the structure of the model is not necessarily known a priori. The only concern is to map the input data set to the output data set in such a way that the output of the model and the output of the modelled system are close. There are several linear and nonlinear black-box model structures available to choose from, e.g., auto-regressive exogenous (ARX), auto-regressive moving average exogenous (ARMAX) and output error (OE), which have traditionally been useful for representing dynamic systems. The model structures vary in complexity depending on the flexibility needed to accommodate the dynamics and noise in the system.

The grey-box model is typically developed using a known structure of the system (but not the exact composition of physical components) with unknown parameters. The parameters are then estimated in a similar way to those in the black-box model. The grey-box model is, thus, a combination of white-box and black-box models, allowing more flexibility in parameter estimation than the white-box model and more physical understanding of the developed model than the black-box model.

3 A quick look into the dynamic equivalencing for bulk transmission systems

Dynamic equivalencing problem is almost old as considerations of computer application to solve power system problems. The focus in the past was on equivalencing a part of large transmission systems. A large number of works was devoted to this problem. Some notable ones were presented in references [1, 2, 3, 4], while industrial approaches for dynamic equivalencing were surveyed in [5]. Synchrony, as a generalization of the concept of slow coherency, was also considered [6]. Obviously the coherency approach was considered as the most reliable for dynamic equivalencing (more details on this approach can be found in the book [7]). Work presented in [8] considers various aspects of identification approach and how they could be combined to form improved dynamic equivalents using grey-box approach.

4 A review of dynamic equivalencing of active distribution networks

In the past, due to the passive nature of distribution networks operation (no DGs connected at the distribution level) the focus, with respect to the dynamic equivalencing of distribution networks, was on aggregation of dynamic loads and load tap changer dynamics for stability studies [9, 10, 11]. There is an obvious gw=rowing interest in dynamic equivalencing of active distribution networks. To this purpose, an extensive literature search was conducted and the results are summarized in Table 1. Note that conference papers are not included in the Table since their content can be easily found in the theses reported here.

Table 1: Summary of the literature search results

Reference(s)	Type of document	Approach
[24]	Journal paper	Coherency (Prony) + identification
[13, 14]	PhD thesis [14], Journal paper [13]	Model reduction (Hankel norm, SVD)
[21, 22, 23]	PhD thesis [22], Journal paper [22, 23]	Identification (grey-box)
[15]	PhD thesis	Identification (black-box)
[18, 19]	PhD thesis [19], Journal paper [18]	Model reduction (modal)
[17]	Journal paper	Coherency
[16]	PhD thesis	Coherency
[25]	PhD thesis	Six-step procedure
[26]	Report	All

Probably the first work considering, although not explicitly, the problem of dynamic equivalents of ADNs is the one reported in [12]. This work focused on the impact of DGs on transmission system stability. It was argued that a simplified model of ADNs must represent the aggregate load of the distribution feeder and the aggregate generation on that feeder and proposed a simple approach to extend the previously used models to include the effects of the distribution system transformers and introduce an equivalent load and generator. However, the details on how the equivalent model is formed are not provided in [12].

Similarly to [12], the works presented in [13, 14] also focused on the impact of DGs on bulk transmission system stability. A dynamic equivalent of an ADN using Hankel norm approximation is proposed in these references. The model was based on calculating the specific operating point data using the load flow calculation. A linearized model is produced by combining the state space model of the generator and the model of the network into one linear model. The model reduction is then performed using Hankel norm approximation based on the specified error boundary. However, the dynamic equivalents produced are valid only for a given operating condition. Therefore, the procedures for obtaining dynamic equivalents need to be repeated for different operating conditions.

The system identification approach was used to develop a dynamic equivalent of an ADN in [15]. This approach treated the ADN as a black box, due to the lack of detailed information on the network structure and parameters. The voltage and frequency are used as the input, and real and reactive power as the output. The result is a state space and auto-regressive ARX model. This method offers simplicity of implementation as there is no need for detailed information about the network. However, the equivalent model produced is highly dependent on the type and location of the disturbance.

A coherency approach for ADN dynamic equivalencing was considered in [16] for transient and small signal stability. It improves over existing coherency approaches by using the time domain decomposition of state variables to determine the coherent groups and to obtain the parameters of equivalent generators.

A coherency approach was also considered in [17] and Prony analysis was used together with support vector classifier to determine coherent groups of generators. The equivalent was built for specific type of dynamic studies (frequency stability).

A related problem of dynamic equivalencing of microgrid was considered in [18, 19]. The proposed method builds upon previous approaches for dynamic equivalencing of bulk transmission systems and modal approach was used to this purpose.

A non-linear dynamic model reduction technique for distributions system dynamic equivalencing was proposed in [20]. System reduction is based on based on covariance matrix (as an extension of empirical Grammians) and it is combined with artificial neural networks (black-box) to form the equivalent. Surprisingly, although very recent this work does not consider DGs connected to distribution network but only load dynamics was taken into account.

The promising approaches are the ones presented in [21, 22, 23]. The grey-box model structure is proposed to represents the dominant behaviour of the ADN system only, and leaves the mismatch part of the system to be approximated by an optimization method. Assumed equivalent model structure of the ADN comprises a converter-connected synchronous generator in parallel with a composite load model. Figure 1 illustrates the dynamic equivalent proposed in these works. The real power and reactive power are the output sand the voltage and frequency the inputs to the equivalent model. All the input and output data are measured at the point of connection of the ADN to the transmission system.

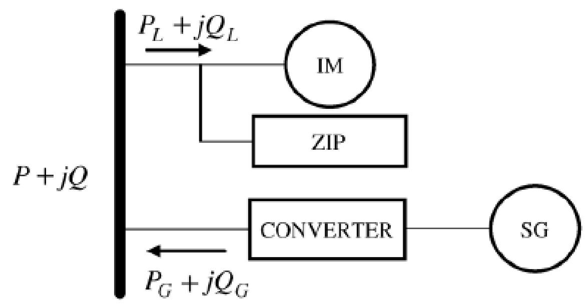

Figure 1: Dynamic equivalent of ADN considered in [21, 22, 23].

The following assumptions were made in developing the equivalent model of [21, 22, 23]:

- the converter-connected generator model includes a third-order synchronous generator model and a full converter model,
- the composite load model is represented by constant impedance, constant power and a constant current load model (ZIP load model), accounting for the static load part, connected in parallel with an induction motor model accounting for the dynamic load part,
- the mechanical torques of both generator and induction motor are assumed to be constant.

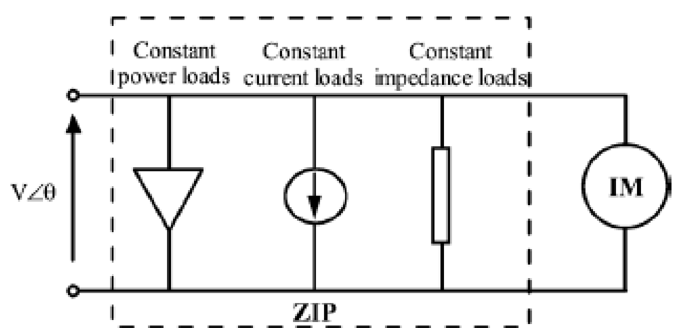

Figure 2: Dynamic equivalent of the ZIP-IM model [21, 22, 23].

The proposed converter-connected generator model can be used to represent micro-turbines and wind turbines, especially the direct drive synchronous generator type. The third-order model of synchronous generator was chosen as it is

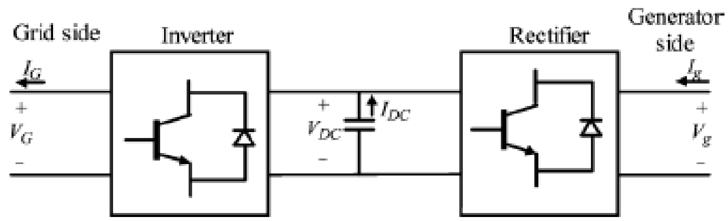

Figure 3: Back-to-back full converter model [21, 22, 23].

adequate to represent the dynamic behaviour of a synchronous generator while preserving the low order of the overall equivalent model. The simple converter model used preserves its dynamic characteristics, represented by the DC-link equation and adequately models its main operational principle, i.e., that the real power flowing through the converter is balanced. The equivalent circuit for the ZIP-IM load model is shown in Fig. 2. The dynamic part of the model is represented by the internal voltage relationships of the induction motor. The synchronous generator interfaces with the grid via a back-to-back full converter as shown in Fig. 3. The real power flow through the converter is balanced via the DC-link (the capacitor linking between inverter and rectifier).

The parameter estimation procedure is displayed in Fig. 3.

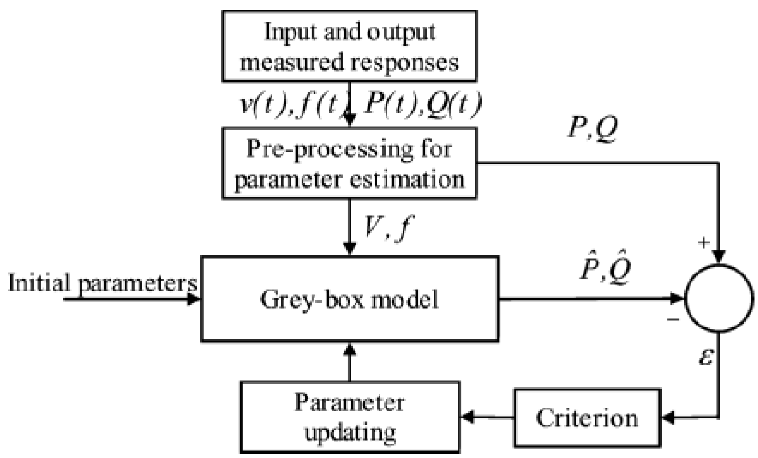

Figure 4: Parameter estimation procedure [21, 22, 23].

The Levenberg-Marquardt algorithm that minimizes the sum of the squares of the distances (Euclidean) between data points and the fitted curve was used for parameter estimation as it is both fast and effective.

Overall, the approach of [21, 22, 23] results in a seventh-order non-linear quasi state space format.

Reference [24] offers an attractive and engineering sound solution, in practical use by the utilities across WECC (formerly WSCC) in the USA. The solution involves following steps:

- Represent transmission system at connection points as large machine (an infinite bus) as illustrated in Fig. 5,
- Make step changes in voltages and frequencies at the connection points and record active and reactive powers as indicated in Fig. 5,
- Use Prony analysis to determine transfer functions and form the equivalent model as illustrated in Fig. 6,

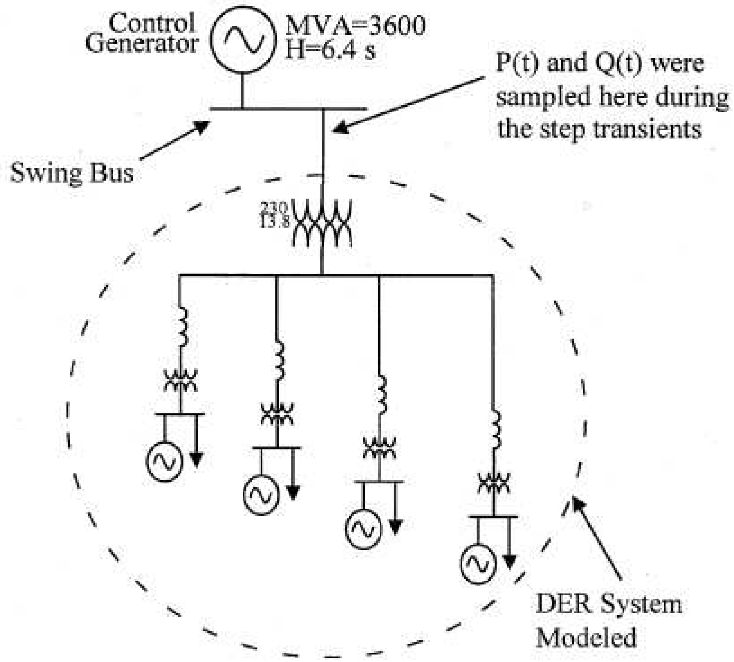

Figure 5: System signal generation [24].

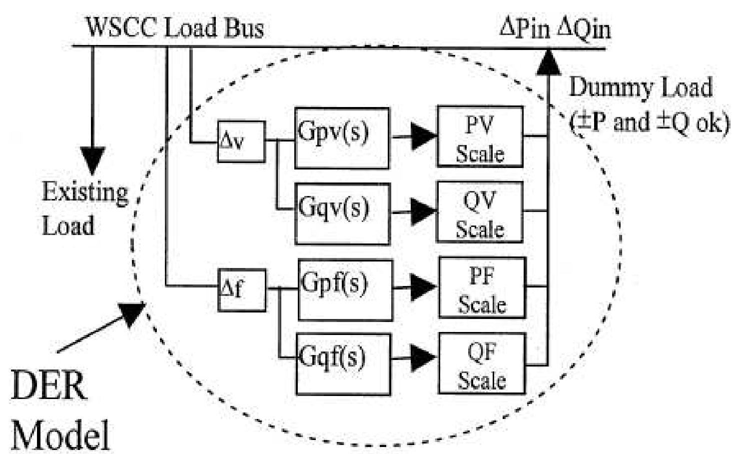

Figure 6: ADN equivalent model [24].

The work presented in [25] suggests the six-step procedure to derive the equivalent. The methodology is displayed in Fig. 7.

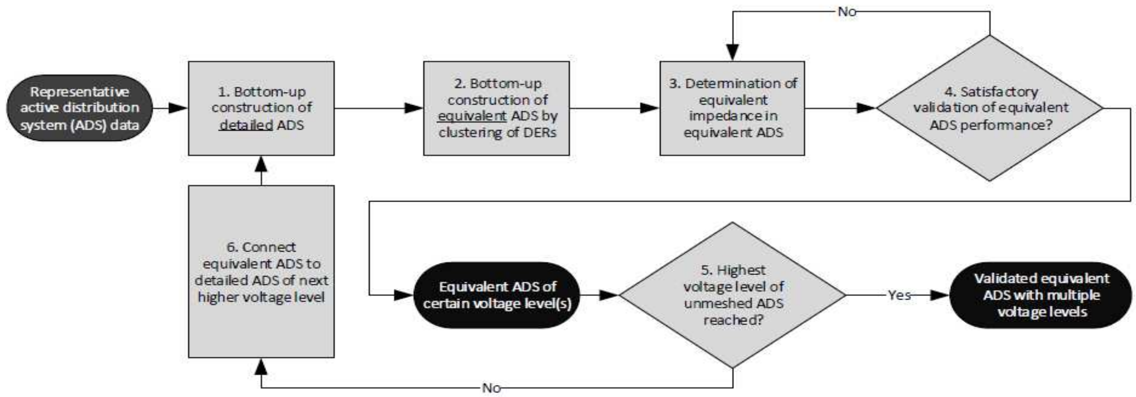

Figure 7: A six-step methodology to derive dynamic equivalent of an ADN [25].

As illustrated in Fig. 8 each type of DG is represented by an equivalent (aggregated) generator and together with the equivalent network impedance Z_{eq} and aggregated load form the equivalent of an ADN.

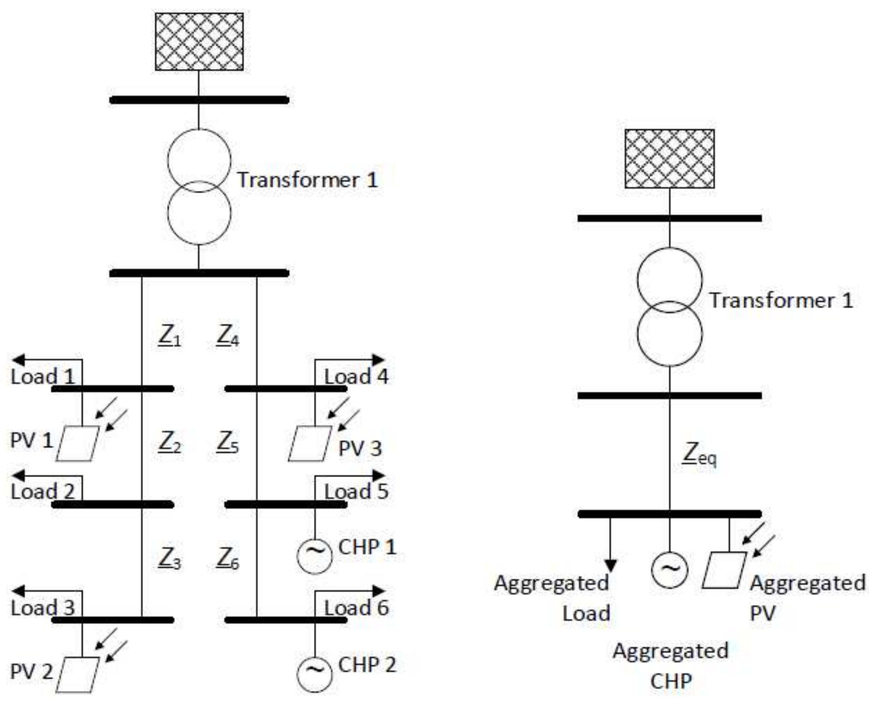

Figure 8: Detailed (left) and equivalent (right) ADN [25].

The methodology involves the following steps:

1. A detailed model of an ADN is created first,
2. DGs are clustered and represented by its dynamic equivalent (including their controls),

3. The equivalent impedance is then estimated based on the input data and iteratively adapted until the equivalent active distribution system (ADS) performance is satisfactory,
4. As long as the highest voltage level, below which all networks are operated radially (unmeshed) is not reached
5. The obtained equivalent ADS is connected to the detailed model of the ADS of the next higher voltage level.

NOTE 1: Most of the approaches presented in this section were also included in a recent CIGRE report [26] and related earlier review [27], except most recent ones [18, 19, 17, 16, 25, 20] and two older ones presented in [12, 24].

NOTE 2: This short review presented only approaches (available to the author) that in the author's view, at the time of report writing, offer attractive solutions. Other methods, summarized in Table 1, may reveal to be equally attractive in future considerations.

5 Conclusions and recommendations

Based on extensive literature search and analysis the following conclusions can be drawn:

- There is a growing interest in dynamic equivalencing of ADNs confirming the importance of the problem,
- A number of proposed approaches build upon previously proposed ones (most notably modal and coherency approach) for dynamic equivalencing of external system in bulk transmission systems with some attempts to improve previously proposed approaches,
- It appears that grey-box identification approach offers advantages over other proposals since it **allows embedding the knowledge of distribution system in defining the structure of the equivalent**,
- New type of loads are somewhat left unconsidered in all existing approaches.

Recommendations for future research can be summarized as follows:

- The grey-box identification approach of [21, 22, 23] appears to be most promising and is worth of further considerations. The focus should be on its characteristic that **allows embedding the knowledge of distribution system in defining the structure of the equivalent**. The next steps, with respect to this approach, could be organized as follows:
  - start with developed generic model and further investigate how it fits specific systems and problems. This is particularly important for voltage stability problems since left unexplored in [21, 22, 23] and important system characteristics to be retained in the equivalent differ with respect to angle stability problems.
  - the generic model of [21, 22] was validated in [23] through small and large disturbance studies using a small (nine-bus) system model. The model needs further validation using larger, and more realistic, system models.
  - check (and possibly extend) the model in case of presence of different composition of DGs. The work [23] offers some results for different composition of SGs, FSIGs, Dfigs, and CCG. The results obtained show that the model works very well with the percentage of best fit between 80%?93%. It would be interesting to check how the model could be modified and this percentage be improved.
  - check the impact of changing ADN conditions (topology, load profiles, DGs penetration, etc.) and possibly extend the model in order to be valid for a wider system conditions.

– consider other parameter estimation techniques (other then the Levenberg-Marquardt algorithm).

- New load types should be considered in the context of grey-box identification approach. In this respect a recent work on load modelling [28] could prove useful. For example, plug-in electric vehicles can be considered as both load and generation and are to be investigated in dynamic equivalencing.
- Dynamic model reduction approach of [20] would be interesting for checking its applicability for ADNs dynamic equivalencing.
- Some other dynamic model reductions techniques, proposed recently in power system literature or developed in other research fields could be also of interest. To this purpose a recent work presented in [29] could be a good starting point.

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