MODEL REDUCTION OF DISTRIBUTION NETWORKS WITH DISPERSED GENERATION

Sylvain MARTINO    Miguel FONTELA    Christophe ANDRIEU
EDF R&D- France    Raphaël CAIRE / Nicolas RETIERE    SCHNEIDER ELECTRIC.S.A-France
Tuan TRAN QUOC / Nouredine HADJSAID    GIE-IDEA / LEG-ENSIÉG - France
fontela@leg.ensieg.inpg.fr

INTRODUCTION

Since the beginning of the 90s, new political and technical orientations have caused changes in electricity networks. One can mention: Kyoto Protocol which imposes the reduction of greenhouse effect gas, Liberalisation of the energy market, Emergence of Dispersed Generators (DG) integrated to distribution networks.

This deregulation of electricity market and new energy politics give the opportunity to connect more and more dispersed generators to the distribution network. These new actors constitute new energy sources. The DG integration in the network presents several effects on the system operation. Electric networks were designed for an energy transfer from the centralised power plants to the customers through the transmission and distribution networks in an unidirectional flow. Today, DG can change this flow direction and impact on the whole system operation. During the past years much attention has been given to the impacts of dispersed generation (DG) installed on the grid [1] and [2]. Thus, amongst the impacts, one can mention:

- Changes in the voltage level
- Variation of short-circuit currents
- Modification of the protection behaviour
- Increase of harmonic pollution in case of power converters for DG connection.
- Modification of the system stability

Of course, large amount of these generators will increase the order of the mathematical model which describes the behaviour of the power system. This could be problematic in different studies such as, impact studies, optimal control, protection scheme or real-time energy management systems design. In this new context of Dispersed Generation, reduced models are necessary to simplify studies.

In this paper, a model reduction approach is proposed to study impacts of LV dispersed generators integration on the distribution system [1]. The main objective is to reduce the order of a LV network for different loads and generation configuration. First of all, the reduction methods which are applied to power systems are detailed. Then, a reduction method of LV network models is proposed in two domains (static and dynamic). The static case is based on load aggregation techniques. The results given are compared with non reduced simulations for different load and dispersed generation configurations.

The dynamic domain reduction is carried out in two ways: first, classical mathematical methods for modal order reduction are applied to LV network. On the other hand, a reduced order model is deduced from a network oriented method called “dynamic equivalents” method. In both cases, reduced and completed models are compared for the same operating conditions.

Finally, the static reduction methodology is applied to study the influence of the reduced model in a DG impacts study on voltage profile.

STATIC DOMAIN REDUCTION

The static reduction of the distribution network was directly inspired by load aggregation method [3]. It should be noted that only the most usual and classical network components were considered: static loads, induction motors, and synchronous generators. Power electronics elements were totally ignored because they require dedicated reduction methods which were not in the scope of this paper [4].

Static load aggregation:

Static loads are traditionally represented by an exponential model in which the active and reactive powers depend on voltage and frequency [5]. In this study, the frequency is assumed constant. So the active and reactive load power is expressed by:

\[ P(V) = P_0 \left( \frac{V}{V_0} \right)^{np} \]  \hspace{1cm} (1)

\[ Q(V) = Q_0 \left( \frac{V}{V_0} \right)^{nq} \]  \hspace{1cm} (2)

The subscript 0 identifies the values of the active and reactive powers when the voltage is equal to \( V_0 \). \( np \) and \( nq \) are exponents that describe the voltage dependence of the load. They can be defined as derivatives of the active and reactive power with respect to voltage:

\[ np = \frac{dP}{dV} \frac{V}{P} \]  \hspace{1cm} (3)
Based on this modelling, it is possible to aggregate multiple loads in a single one [6].

a) Parallel load aggregation

Let us consider n loads connected in parallel. For a load i, powers can be written as

\[ P_i(V) = P_0 \left( \frac{V}{V_0} \right)^{\nu qi} \]  
\[ Q_i(V) = Q_0 \left( \frac{V}{V_0} \right)^{\nu qi} \]  

The total active and reactive powers are given by

\[ P = \sum_{i=1}^{n} P_i = \sum_{i=1}^{n} P_0 \left( \frac{V}{V_0} \right)^{\nu pi} \]  
\[ Q = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} Q_0 \left( \frac{V}{V_0} \right)^{\nu qi} \]  

Thus, it is possible to aggregate all the parallel loads into one defined by:

\[ P(V) = P_0 \left( \frac{V}{V_0} \right)^{NP} \quad NP = \sum_{i=1}^{n} \frac{P_0 \nu pi}{P_0} \]  
\[ Q(V) = Q_0 \left( \frac{V}{V_0} \right)^{NQ} \quad NQ = \sum_{i=1}^{n} \frac{Q_0 \nu qi}{Q_0} \]  

b) Series load aggregation

A power system has series impedance between buses (sending node, subscript s) and loads (receiving node, subscript r). To derive a load model at the sending node it is necessary to consider the effect of such impedance (figure 1). A method propose in [6] uses the aggregate load model at the receiving end to create a load model at the sending end in the form of (1) and (2). Parameters (P_s, Q_s, nps and nqs) are calculated from the receiving end model (P_r, Q_r, npr and nqr) and the parameters of the series impedance (R and X) (see equations (11) to (14) below).

The expressions of the power exponents of the equivalent static load model at the sending end are given in equation (13) and (14).

\[ nps = \nu pr \]  
\[ nqs = \nu qr \]  

Induction motors aggregation:

Induction motors are usually represented by the equivalent circuit given in figure 2 if the stator resistance is neglected and all the leakage flux are assumed to be located at the rotor.

Xm is the magnetising reactance, Xr is the total leakage reactance and Rr is the rotor resistance. The rotor slip is indicated by g. Two order reduction methods are used depending on the way the motors are connected to the power system.

In the general case, the powers of each individual motor are

\[ nq = \frac{dQ}{dV} \frac{V}{Q} \]  

(4)
first evaluated. This evaluation requires the motor slip determination. Then, all the electric powers of the different motors present in the network are summed. If the motors are connected in parallel, an aggregate induction motor is computed. Its electrical and mechanical characteristics are a combination of individual ones [7].

Generators aggregation:

The generators present in the network can be considered with two different behaviours:

a) The generator can be considered as a reverse PQ load where P and Q are constants and negatives. This corresponds to the general case of a static load with \((np=0)\) and \((nq=0)\) and \((P_0<0, Q_0<0)\). The aggregation of generators is carried out in the same way that it was shown for static loads and it corresponds with an addition of powers.

b) The generators can be considered as reverse PQ load where P is generally kept constant by the regulation and Q is voltage and/or excitation current dependent. In this paper, the first behaviour has been considered because it can be found in most new DG sources based on renewable energies. Indeed, these new DG sources have usually an energy store element to supply a P and Q constants to the grid. But, in any case, it is possible to compute the total generating active and reactive power by summing individual powers. So the aggregation have been made in the same way that it was studied for induction motors, summing the individual power of each generator.

Transformer aggregation:

The transformer model is shown in figure 3:

Therefore, the transformer is considered as an association of a series impedance \((r_s, l_s)\) and a parallel impedance \((R_{fer}, L_m)\). Aggregation methods are the same as these presented for static loads. So, the transformer is aggregated as a series element and then the parallel load is included to do a correction of active and reactive powers.

\[
P_{HTA} = P_{BT} - P_{fer} \tag{15}
\]

\[
Q_{HTA} = Q_{BT} - Q_{Lm} \tag{16}
\]

Final results

The order-reduction methodology is applied to the low-voltage (LV) network which is shown in the figure 4. This last is formed for different static loads and two electric machines: a synchronous generator and an induction machine which is working as a load. The MV/LV transformer is a 20kV/400V transformer and it links the LV branch to the MV distribution network.

In conclusion, the aggregation model and the complete one ARENE simulation are very closed in the case of active power with a maximum error of 2.3%. On the other hand, in the case of reactive power the error is around 5%. This error is caused by the series aggregation of the transformer and the parallel association correction.

DYNAMIC REDUCTION

In the case of the dynamic reduction, two approaches are carried out. First, an approach based on modal reduction method is presented. This approach has been successfully applied for control model reduction [8],[9]. Secondly, a reduced model based on a dynamic equivalent approach is given [10].

Modal Reduction Analysis

Order reduction method consists in eliminating modes which have little influences on the system operation for the considered conditions. This method requires a state-space representation of the network. Modes are eliminated by
using two standard methods implemented in Matlab Robust Control toolbox: Moore method [11], [12] and Hankel method [13].

This approach is applied to the reduction of the LV network described in figure 5. The LV network contains two synchronous generators: GED (40 kVA) and GEN (100 kVA). This LV network operation has been simulated in Eurostag (a power simulation software from EDF).

Eurostag gives us the needed linearized state-space representation of the system. The state-space system is a multivariable system where the currents (I_D current in axes D and I_Q current in axes Q) of each generator are considered as output variables and the voltage and torque regulations as input variables.

The order of the Moore and Hankel reduced models are equal. Thus, the model order decreases from 12 to for the complete model to 9 for both reduced models. The frequency response of the reduced and complete models are compared in figure 6. The step response of complete and reduced models is given in figure 7.

The comparison of complete and reduced step and bode response shows that both reduced models are very close to the complete model behaviour and in the study case no one is better than the other. Thus, it seems that there is no significant difference between both reduction methods.

This method is particularly interesting to study the system stability. Indeed, the situation of the system eigenvalues defines the stability. Thus, this eigenvalues are computed form the state-space matrix as its eigenvalues. The system is unstable if one of these eigenvalues has a positive real term. As it is shown in figure 8, all the eigenvalues have a negative real term.

However, in the operation of the electric networks, some events like a short-circuit can cause instabilities. The gain of generators regulations could be modified to ensure the stability. The coefficients of the state-space matrix can be changed in a way to restore the system stability.
Dynamic Equivalents

A reduced-order dynamic model is computed by aggregating, first, all the static loads, and then, all the generators (see figure 9). The static loads aggregation was made by the application of expressions shown in the static domain reduction.

\[ p_{eq} = \frac{1}{S_{nom_{eq}}} \sum_i S_{nom} p_i \]  
\[ S_{nom_{eq}} = \sum_i S_{nom} \]  

where Snom_{eq} is the rating of the equivalent machine, equal to the sum of the ratings of the individual machines.

This method is applied to the LV network described in figure 4. This LV network has been placed in an urban network (see figure 10).

This MV network is a 4509 kVA network with 5587 LV customers and 6 MV customers. These different kind of loads are distinguished in figure 10. The LV loads belong to different MV/LV public distribution networks and MV loads are connected directly to distribution network at 20 kV.

The complete and reduced-order current time responses are shown in figure 11 when a 3phase short-circuit occurs at the secondary of the HV/LV transformer. In conclusion, the currents of the short-circuit at the secondary of the HV/LV transformer have a temporal behaviour which is similar for the complete structure and the reduced structure.

DG IMPACT STUDY

In this section, the authors propose an application of the reduction methods for studying LV-DG impacts on the voltage profile. The voltage level is one of the different points of quality that the electric utilities have to assure to the customers. So, it is necessary to guarantee that the penetration of DG does not change voltage buses values out of the technique specifications.

The static reduction methodology is applied to the French urban network that it is shown in figure 10. Furthermore, 11 LV branches (figure 5) have been placed to carry out the
A study of voltage profile is made and a comparison between the complete network and the reduced static network is shown in figure 12.

The comparison of the voltage profile between the complete network and the reduced network is made for all the buses of the MV urban network. The error between both voltage levels does not exceed of 0.3% in the worst of the cases. Therefore, this result constitutes a check point to validate and generalise the reduction methodology in order to apply it in voltage impact studies.

CONCLUSIONS

Different methodologies have been applied to build a reduced-order model of an electric network. The study has considered the static and dynamic domains. The static reduction help us to evaluate the DG impacts. Usually in LV networks, there is not a complete information about all the loads which are connected to the grid. If electric powers of each element are known, a simulation can be carry out from the proposed reduced model. Furthermore, the total computation times for both simulations are very different. Thus, the complete model reduces in 8 minutes the total simulation time (this time includes all processor blocks of ARENE simulation). Finally, the dynamics equivalents methods is useful to obtain a more physical reduced model in the form of an equivalent generator in parallel with a load which is the aggregate of all load in the considered network. This last reduced model is especially interesting because it could be used to decrease the complexity of different studies such as, impact studies, optimal control, protection scheme or real-time energy management systems.

In conclusion, the two reduction methodologies that have been applied are specific of different applications. However, the dynamic equivalents seems more generic.

REFERENCES