DYNAMIC EQUIVALENTS OF ACTIVE DISTRIBUTION POWER SYSTEMS FOR INVESTIGATION OF TRANSIENT STABILITY

Traian N. PREDA, Kjetil Uhlen
NTNU – Norway
Traian.Preda@elkraft.ntnu.no

Dag Eirik Nordgård, Trond Toftevaag
SINTEF Energy – Norway

ABSTRACT

In Norway distribution networks are evolving rapidly into active systems due to the increasing number of connections of small scale hydro generation units. As most of the distributed generation is based on synchronous technology their dynamic response on the bulk transmission power system cannot longer be neglected. In this paper a method for power systems reduction and aggregation of generators is applied to obtain dynamic equivalents of distribution power systems with DG units. Criteria to validate this method for distribution power systems are proposed.

INTRODUCTION

Worldwide, the share of the distributed generators (DG) connected to distribution power systems (DPS) is continually increasing. In Norway small scale hydro units and wind turbines are the dominating generation technologies. As their number increases, distribution and transmission network operators are starting to become aware on the risks DG may pose on the stable operation of the national power system. These risks may also be of concern outside the borders of the national power systems, especially for the systems within deregulated energy markets. To address these issues in Europe, the association of transmission system operators - ENTSO-E- is currently issuing a common grid code [1] which covers different aspects related to the integration of DG units. Although connection guidelines are available, studies related to the impact of increased share of DG on the transient stability of bulk transmission systems during disturbed operation are necessary but very rare. Also often, simulation models for distribution systems representation as a simple feeder can be out of date as networks are becoming active power systems, [2]. A complete representation of DPSs can be inefficient as these systems are radial grids spread over large areas and having a large number of power systems components to be modelled. Therefore in order to obtain a valid response of the transmission power system (TPS) during disturbances, TSOs will need to have simplified and still accurate representations of DPSs, which will not affect the computational time of the power system state estimation. [2, 3]

In this paper an algorithm for network reduction and aggregation of synchronous generation based DG units is applied for a benchmark DPS. The iterative steps of the algorithm and their implementation into a simulation platform are described in detail. In order to validate the reduced models, criteria based on voltage response (at the interconnection point between DPS and TPS) and transient stability margin preservation are considered.

The paper is structured as in the following:
In the first section is presented an overview of methods used for network reduction and aggregation of synchronous based generator units. Second section describes the benchmark power system used to obtain the dynamic equivalent of DPS and to validate the method based on the considered criteria. The third details the algorithm for DPS reduction and aggregation of DG units and the implementation in DIgSILENT Power Factory 14.1.6©. In the last two sections, results are presented and the main conclusions of this research are discussed.

DYNAMIC EQUIVALENTS FOR POWER SYSTEMS

Dynamic equivalents for power systems are very well established theories especially for large interconnected power systems, but it can also be applied to active distribution power systems as these systems are generally sparse and starting to accommodate an increasing amount of small scale generation units. The basic idea is to separate the power system into three main areas depending on what is the impact after a disturbance occurs, [4]. According to [4-6] these main areas are: the area under study or the internal area, the external area and a remote area. Figure 1 illustrates this differentiation.

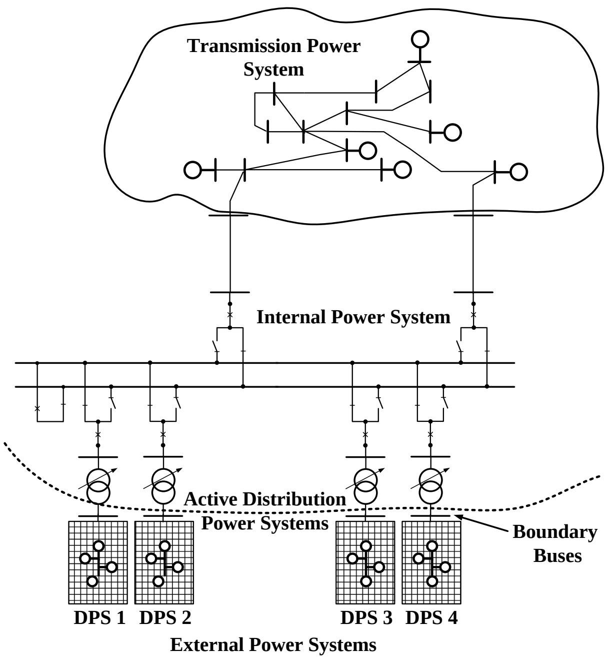

Figure 1 Separation of TPS and DPS into internal and external areas

In this study, the internal area is represented by the MV busbar of the HV substation were the DPS is interconnected with the TPS. The external power system is in this case the entire DPS. A remote area is not defined as the overall response of the entire DPS is of interest but it is considered in the transient stability analysis of TPS. The boundary buses are the MV buses of interconnection transformer of DPS with the HV substation and the PCCs of DG units connected in each active DPS.

To model the dynamic equivalency of DPS, the following steps are considered [6]:

1. Identification of coherent DG units in the DPS after a fault event in the internal area
2. Network reduction of DPS
3. Dynamic aggregation of coherent groups of generators

The proposed algorithm was implemented in DIgSILENT Power Factory 14.1.6© simulation platform, using DIgSILENT Programing Language scripts [7]. This algorithm has a generalized character, so it can be applied to a TPS with more than one active DPS (with high penetration of synchronously based DG units). Figure 2 summarize this algorithm.

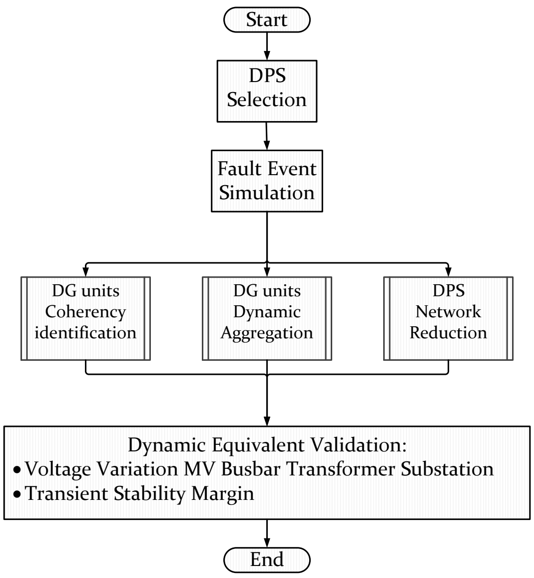

Figure 2 Algorithm to obtain the dynamic equivalent of DPS

BENCHMARK DISTRIBUTION POWER SYSTEM AND HV SUBSTATION TOPOLOGY

The topology of the benchmark DPS and HV substation is illustrated in Figure 3. It consists of 4 voltage levels: 0.69, 6.6, 22 and 132kV and 11 small scale hydro units based on synchronous technology equipped with exciters and governors. For simplification, an IEEE ESAC8B model was adopted to represent the AVR and excitation system, and a HYGOV model from simulation platform library [7] was used to represent the hydro governor. The total length of the DPS lines is 51.55km. The point of interconnection with TPS is in the busbar TRAFO_TPS which is modelled as a double busbar with tie connection. The topology of the busbar TRAFO_TPS is depicted in Figure 3. A 132/22kV transformer interconnects the DPS with TPS. The model of the TPS is simplified by considering the nearest medium hydro unit (P_G=*35*MW), a local industrial load (P_L=*0.721*MW) and a strong slack bus with S_k''=*6000*MVA.

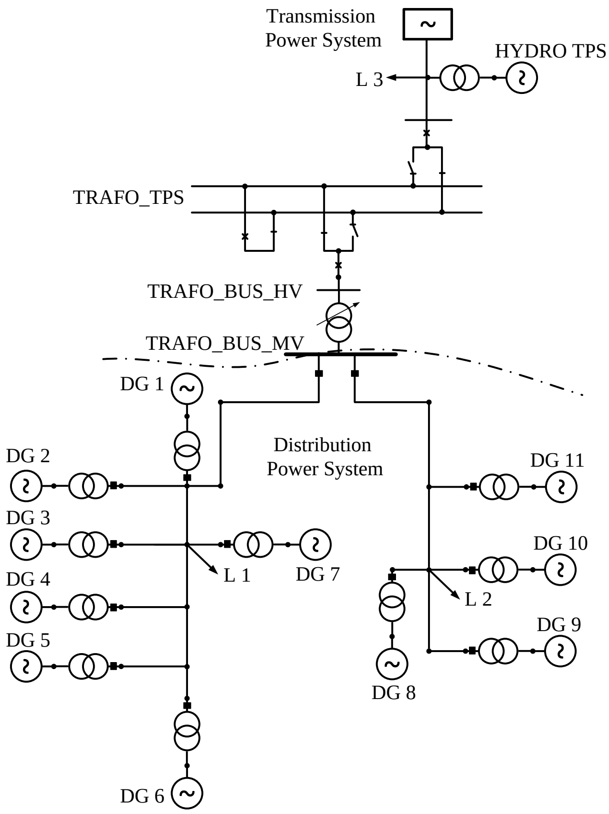

Figure 3 Benchmark DPS topology

Identification of coherent DG units in the DPS

For the identification of coherent DG units a mechanical coherency method based on the Euclidean distances between DG units is applied, as described in reference [8]. The main idea behind this method is to identify the DG units which are coherent or swing together after a fault occured in the internal area [9]. For this a bolted three phase short circuit is applied at TRAFO_BUS_MV with a duration of 150 ms. In the post-fault period the rotor angle of all DG units were recorded and the Euclidean Distance – ED (as in equation 1) between DG units *i* and *j* was computed in order to identify the cluster of coherent generators. [8]

$$ED_{i,j} = \sqrt{\sum_{t=t_1}^{T}\left(u_i(t) - u_j(t)\right)^2} \qquad (1)$$

In this study, the criteria considered for mechanical coherency identification are the ones presented in reference [9]. According to [9], two synchronous generator units are considered to be coherent if the distance between their rotor angle variations is smaller than 0.17 radians or 10 degrees.

Further, this method is applied for the benchmark DPS depicted in Figure 3 for a fault event occurring at bus TRAFO_BUS_MV.
Figure 4 presents the rotor angle variations for all DG units connected in the benchmark power system and Figure 5 depicts de clustering process of the DG units.

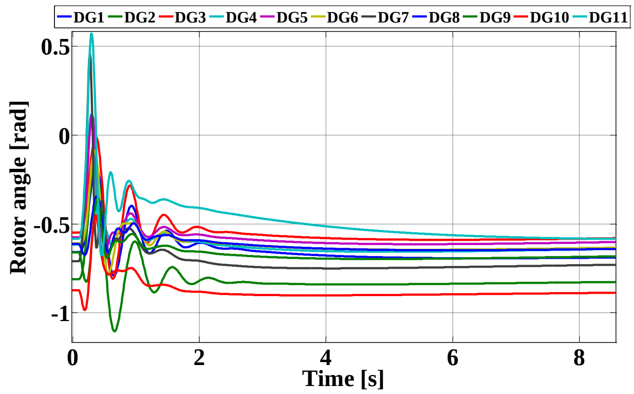

Figure 4 Rotor angle variation after fault emerged at bus TRAFO_BUS_MV

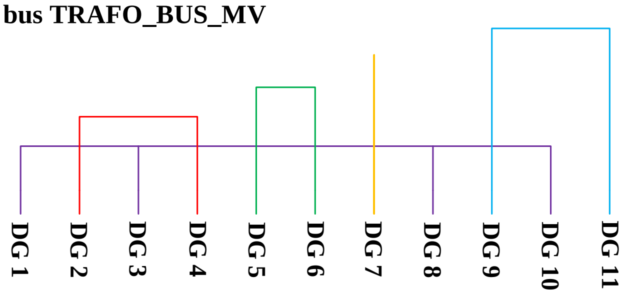

Figure 5 Dendrogram of DG units clustering

Network reduction of DPS

The network equivalent was estimated using an Extended Ward equivalent because this method can roughly preserve the original DPS network response both in terms of active and reactive power flows, as discussed in [10].

Dynamic aggregation of coherent groups of generators

After the coherent groups of generators are identified, the equivalent sets of generators-transformers are formed and the new equivalent parameters for these sets and their correspondent controllers are computed. The new parameters for the equivalent synchronous generators and controllers' parameters are produced according to the method presented in [11].
Figure 6 presents the resulting dynamic equivalent of the benchmark DPS based on an Extended Ward network reduction of the original power system.

METHOD VALIDATION

Two criteria are considered for validating the dynamic equivalent of the benchmark DPS. First one refers to the preservation of the voltage magnitudes and angles variation at the bay busbar were DPS is connected. Figures 7 and 8 present these two responses for both original and the dynamic equivalent of the benchmark system.

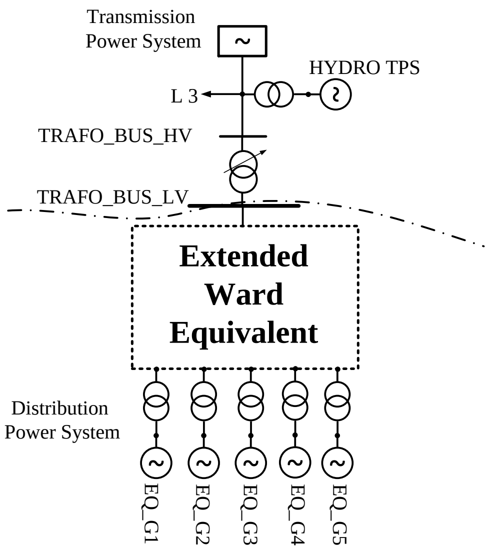

Figure 6 Extended Ward equivalent of original benchmark DPS for transient stability assessment into bulk TPS

The average error was computed for each of the two series of voltage magnitude and angle variations. For the voltage magnitude variation an average error is 0.0021 was obtained while for the voltage angle the error was 0.0951.
The second validation criterion is the transient stability margin, which gives information about the reserve of decceleration area according to the Equal Area Criterion, detailed described in [6]. According to this reference, the transient stability margin can be defined as:

$$K_t = \frac{t_{CCT} - t_{actual,CCT}}{t_{CCT}} \tag{2}$$

The simulations for both the original and the reduced DPS, showed that the critical clearing time (CCT) was 0.5006s for the original power system and 0.497s for the reduced DPS.
Considering an actual clearing time of 64ms (2 cycle breaker clearing time: 36ms, primary and auxiliary relays times: 28ms) [12], the transient stability margins, K_t, presented in Table I are obtained.

Table I. Transient stability margins

	K_t
Original DPS	0.871
Reduced DPS	0.872

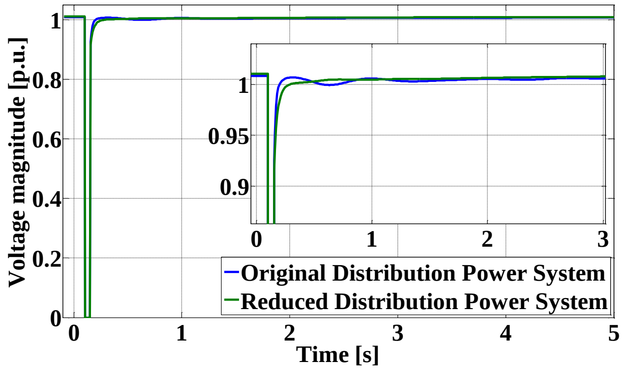

Figure 7 Voltage magnitude variation at bus TRAFO_BUS_MV

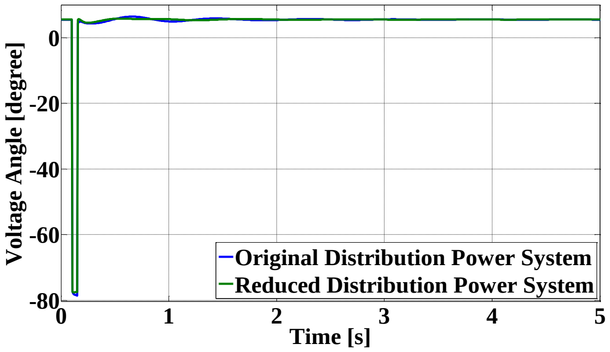

Figure 8 Voltage angle variation at bus TRAFO_BUS_MV

CONCLUSIONS

In this paper methods usually used to obtain dynamic equivalents of wide area TPSs are applied to a benchmark DPS with an increased share of small scale hydro units. The scope is to produce a simulation model suitable for represention of active DPSs in transient stability studies of TPSs by taking in consideration the dynamics associated with DG units connected. In order to reduce the DPS network, an Extended Ward equivalent was used, and to aggregate dynamically the DG units a mechanical coherency method based on rotor angle variation was applied. In order to validate the alghoritm two criteria were proposed. The first looks at the preservation of the voltage magnitude and angle variations at the busbar in the internal area (in this case the MV busbar of the bay transformer where the DPS is connected). These variations are of interest when considering the AVR and load modeling influence on the transient stability study. The second criterion looks at the preservation of the transient stability margins as an important indication of the rotor angle dynamics associated with the synchronoulsy connected DG units. The study have shown that the dynamic equivalent obtained for DPS preserves the original response, in terms of voltage magnitude and angle variations when a fault emerged at the bay's transformer MV busbar. Regarding the transient stability margins, a small increase was observed in comparison with the original one. This small difference is due to the process of aggregation of transient, subtransients and exciter parameters of the synchronous DG units.

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