REDUCTION AND AGGREGATION FOR CRITICAL AND EMERGENCY OPERATION OF DISTRIBUTION NETWORK IN PRESENCE OF DISTRIBUTED GENERATORS

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ABSTRACT

A new type of network namely "Active Network" is foreseen as a relevant evolution of the current passive distribution networks and might be a technically and economically feasible solution to facilitate Decentralized Energy Resources (DERs) interconnections in a deregulated energy market. But one of the difficulties of related studies consists in the small size of Distributed Generator (DGs) and the quantities of algebraic and differential equations resulting from the large number of buses and state variables attached with their control systems. These factors, added to the limited state estimation in distribution networks make it difficult for the Distribution System Operator (DSO) to have online security assessment. This paper presents a hybrid reduction method, which enables the DSO to decrease the number of computed elements and, consequently, the simulation time for distribution network. This reduction should enable also DSOs to facilitate the real time critical and emergency analysis of distribution network in presence of DGs.

I. INTRODUCTION

Being stimulated by many favoured conditions, the amount of DGs installation in distribution network has considerably increased in recent years. With a high level of penetration, they should take their share of responsibility with large conventional power plants. They could also provide flexibility and controllability necessary to support secure system operation. Therefore, this new paradigm namely "Active Network" is foreseen as a relevant evolution of the current passive distribution networks. This type of network allows the DERs to participate to the distribution system operation.

However, the lack of common functions and framework for information and communication systems for the whole future active distribution network stands in the way of the achievement of the required goal. This challenge is partially fulfilled within the INTEGRAL FP6 European project [1]. This latter aims to build and to demonstrate an industry quality reference solution for Distributed Generators (DGs) aggregation level control and coordination based on commonly available ICT components, standards and platforms. Specific functions will be defined and tested into the three major demonstrators which cover three operation states: Normal, Critical and Emergency operations. These functions will be integrated into intelligent agents [7] that are distributed on limited area. They are part of the advanced Distribution Management Systems (DMS) distributed on field. For large distribution network containing thousand of nodes and a large amount of DGs, the information needed to manage and to control for each distributed agent is significant.

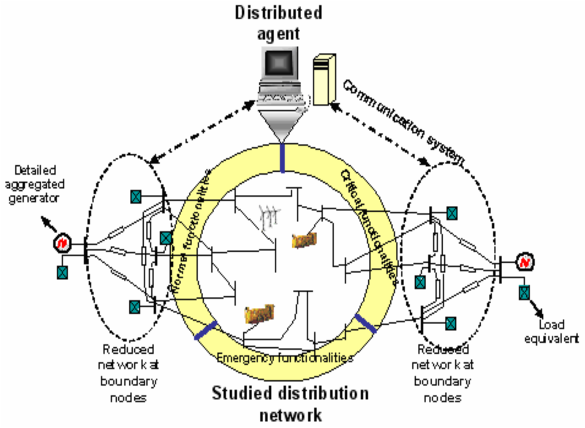

Figure 1. Illustration for equivalent model integrated eventually into distributed agent.

To deal with this problem, apart from improving the performance of ICT system; another solution is to resize the studied network. The large distribution network will be divided into many sub-networks. This division is flexible and normally determined by some specific technical, economical as well as geographical criterions. Each sub-network is controlled by a distributed agent. This agent associates with its studied network, and sees the others sub-network as the reduced networks at boundary nodes. The typical exchange requirement among these agents would be a power equivalent model rather than detailed network data because of the communication and computation capabilities of their ICT devices. Figure 1shows the equivalent model that will be associated with an agent. This model allows the analysis of large distribution network to be practically possible given the limited computer storage and speed at this time.

Furthermore, this model is used in the constitution of the Technical Virtual Power Plan (TVPP) within the European project FENIX [2]. The higher operator levels, like DSO, TSO, could manage the large distribution network with the presence of DGs.

II. NETWORK REDUCTION AND DG AGGREGATION

Important impact on dynamic behaviour of network come from synchronous generators and some kind of wind turbine technologies although the considerable attention is concentrated to new generation technologies, e.g. fuel cells, photovoltaic, biomasses [3]. Because almost renewable generation connected to network via the power electronic interface, their participation to the fault situation is always restrained by the limit setting in order to protect the electronic devices. Furthermore, a great part of generation on the medium voltage network are synchronous generators with the Combined Heat Power usage. In this paper, only synchronous generator type are taken into account. For others types of DGs equivalent, the readers can look at [4].

II.1. Network reduction

Network reduction aims to reduce the number of elements in a large network, so that the reduced equivalent contains smaller amount of nodes and branches than the original network. Many of equivalent method have been developed for both static and dynamic analysis of power systems [5]. However, distribution network differs also from transmission network in the many types of generators technologies. In order to build the equivalent models for the external network including different generation technologies, some additional nodes (each of them correspond a set of different sort of generators) will be created. Then, the set of coherent generator of external network will be replaced by power injection, in a static analyse, or a dynamic equivalent generator, in dynamic analyse, connected to the equivalent nodes.
The hybrid network reduction consists of combination of two static equivalent methods:

1. Elimination of every generator nodes in external network by using Ideal Transformer method.

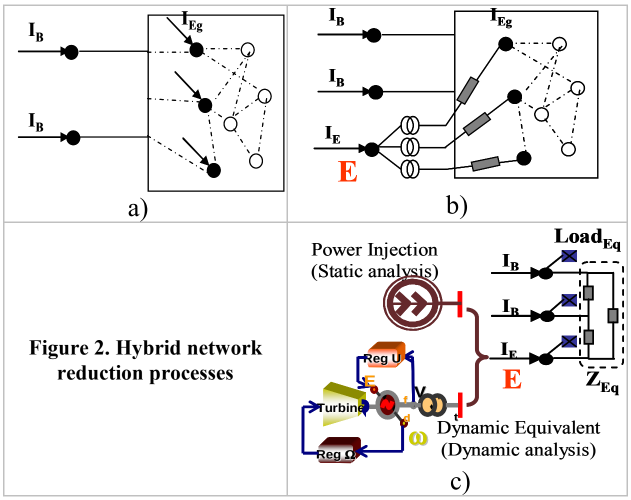

Figure 2. Hybrid network reduction processes

The E-node will be created to replace the generator nodes in the external network. On the basis of power preservation at the equivalent node, the ideal transformers are added to the branches between equivalent node and generator external nodes. Since all the ideal transformer branches have the impedance equal to zero, the set of these branches will be considered as zero power loss networks.
Therefore, the ideal transformers have complex transformation ratios:

$$N_{EgE} = \frac{U_{Eg}}{U_E} \quad \text{and} \qquad I_{Eg} = \frac{1}{N^*_{EgE}} I_E \tag{1}$$

where Eg refer to the generator nodes in external network, E refers to the equivalent node.

The necessary condition for the equivalent is that total injection at the equivalent bus must be equal to the sum of all injection at the external generator nodes:

$$I_E = \sum_{Eg} I_{Eg} \tag{2}$$

The nodal equations of the original network are described:

$$\begin{aligned} I_{Eg} &= \sum_{r\in R} Y_{Egr} U_r + \sum_{Eg} Y_{EgEg} U_{Eg} \\ I_r &= \sum_{r\in R} Y_{rr} U_r + \sum_{r\in R} Y_{rEg} U_{Eg} \end{aligned} \tag{3}$$

where R refers to the set of retained nodes.
Replace (1) and (2) in (3), we have:

$$\begin{aligned} I_E &= \sum_{Eg}\sum_{r\in R} N^*_{EgE} Y_{Egr} U_r + \sum_{Eg}\sum_{Eg} N^*_{EgE} Y_{EgEg} N_{EgE} U_E \\ I_r &= \sum_{r\in R} Y_{rr} U_r + \sum_{r\in R} Y_{rEg} N_{EgE} U_E \end{aligned} \tag{4}$$

Finally, the nodal equations for the reduced network are established:

$$\begin{aligned} I_E &= \sum_{r\in R} Y_{Er} U_r + Y_{EE} U_E \\ I_r &= \sum_{r\in R} Y_{rr} U_r + Y_{rE} U_E \end{aligned} \tag{5}$$

where:

$$\begin{aligned} Y_{EE} &= \sum_{Eg}\sum_{Eg} N^*_{EgE} Y_{Eg} N_{EgE} \\ Y_{Er} &= \sum_{Eg} N^*_{EgE} Y_{Egr} \\ Y_{rE} &= \sum_{r\in R} Y_{rEg} N_{EgE} \end{aligned} \tag{6}$$

2. Elimination of every load nodes in external network by using the Ward-PQ method [4].

Now, consider the generator equivalent node E as a boundary node, the admittance matrix are expressed by (7):

$$\begin{bmatrix} [Y_{EE}] & [Y_{EB}] \\ [Y_{BE}] & [Y_{BB}] \end{bmatrix} \begin{bmatrix} U_E \\ U_B \end{bmatrix} = \begin{bmatrix} I_E \\ I_B \end{bmatrix} \tag{7}$$

where "B" refers to the boundary nodes, "E" refers to external nodes.
Eliminate the load node of external network:

$$\begin{aligned} &\left\{[Y'_{BB}] - [Y_{BE}][Y_{BE}]^{-1}[Y_{EB}]\right\}[U_B] = I_B - [I_E][Y_{EE}]^{-1}[Y_{BE}] \\ &[Y^{Eq}_{BB}][U_B] = [I_B] - [\Delta I_B] \end{aligned} \tag{8}$$

Finally, the equivalent network at the boundary nodes is:

$$[Y^{Eq}_{BB}] = [Y'_{BB}] - [Y_{BE}][Y_{BE}]^{-1}[Y_{EB}]; \tag{9}$$

The additional load connected to the boundary nodes is:

$$\Delta S^{Eq}_{BB} = [U_B]\left\{[Y_{BE}][Y_{EE}]^{-1}[I_E]\right\}^* \tag{10}$$

The reduced network contains finally an additional node E, the supplementary load ΔS^{Eq}_{BB} and branch $[Y^{Eq}_{BB}]$ at boundary nodes (Figure 2c).

II.2. Aggregation of DGs

The proposed aggregation method uses a non-iterative procedure to determine the parameters of the equivalent generating unit, including associated control devices. It is based on the preservation of the coefficient matrices of the generator, excitation, and turbine governor models represented in the time domain.

Let us consider a set of synchronous generators connected in parallel and determine the parameters of the equivalent machine having the same behaviour of the considered set.

The two-axis model in the time domain of the machine can be presented as in [5]:

$$T'_{do}\frac{dE'_q}{dt} = -E'_q + (x_d - x'_d)I_d + E_{fd}$$

$$T'_{qo}\frac{dE'_d}{dt} = -E'_d - (x_q - x'_q)I_q \qquad (11)$$

In this model, the generator is represented by the transient EMFs E'd and E'q behind the transient reactances x'd and x'q. The armature voltage equation is determined by:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} E'_d \\ E'_q \end{bmatrix} - \begin{bmatrix} 0 & x'_q \\ -x'_d & 0 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad (12)$$

where:

Vd, Vq: d and q axis components of terminal voltage

E'd, E'q: d and q axis components of voltage behind transient reactance;

Id, Iq: d and q axis components of stator current;

E_{fd} : field voltage or exciter output

x_d, x_q : d and q axis synchronous reactances

x'_d, x'_q : d and q axis transient reactances

Using (3), the kth machine currents can be written as:

$$\begin{bmatrix} I_{dk} \\ I_{qk} \end{bmatrix} = \begin{bmatrix} 0 & 1/x_{dk} \\ -1/x_{qk} & 0 \end{bmatrix}\left(\begin{bmatrix} V_{dk} \\ V_{qk} \end{bmatrix} - \begin{bmatrix} E_{dk} \\ E_{qk} \end{bmatrix}\right) \qquad (13)$$

or $I_k = A_k V_k - A_k E_k$ (14)

where k= 1, 2….m denote the generators of the coherent group.

The corresponding equation for the equivalent machine (or aggregated machine) is

$$I_e = A_e V_k - A_e E_k \qquad (15)$$

where Ae should have the same structure as the matrix Ak defined by (13);

In order to work in a same reference frame, the terminal voltage phasor Vk expressed in (dk, qk) are converted to the common reference frame (D, Q) moving at synchronous speed.

After the transformation which assures the perseveration of structure matrix, the equivalent parameters of aggregated generators are as following [4][5]:

$$X^e_{(d,q)} = \frac{1}{\sum_{k=1}^{m} a_k \left[\frac{1}{x_{(d,q)k}}\cos^2(\delta_k - \delta_e) + \frac{1}{x_{(q,d)k}}\sin^2(\delta_k - \delta_e)\right]} \qquad (16)$$

where: $X^e_{(d,q)}$ can be synchronous, transient impedance on the axe d,q of corresponding aggregated generator.

With the same analogy, we can have the equivalent parameters

$$T'_{doe} = -\frac{1}{C_{e22}} \qquad T'_{qoe} = -\frac{1}{C_{e11}} \qquad (17)$$

The equivalent parameters of the control systems are estimated with the same perseveration structure principle of their own state matrix [4][6].

III. STUDY CASE

The proposed equivalent methods are tested in a power network including a part of 400kV transmission network, medium voltage network of 63kV and two larges distribution networks of 20kV. In the distribution network, several small synchronous generators that the power varies within the range: 1.2 MVA to 5MVA. The detailed parameters of the branches, load as well as those of the generators are given in [4][6]. This tested network makes it possible to analyse not only the equivalent algorithm, but also to study the operation of the mixed networks containing the large, medium and small size generators.

Two sorts of study will be taken into account through this network.

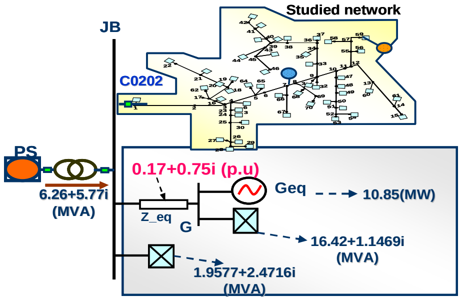

Figure 3. Equivalent distribution network

Firstly, the load flow analysis is carried out for the several distribution feeders supplied by a substation. There are three large feeders including totally 183 nodes. To build a static equivalent model, the feeder C0202 is considered as the studied network and the two remainder feeders will be replaced by the equivalent model.

Figure 3 presents the reduced network. The two feeders are replaced by the equivalent loads and a power injection which represent the sum of all distributed generators in those feeders. The errors of voltage magnitude in the nodes of the studied network with external reduction in comparison with the original network can be observed in Figure 4. These errors are below 0.08% meaning the accuracy of the proposed method.

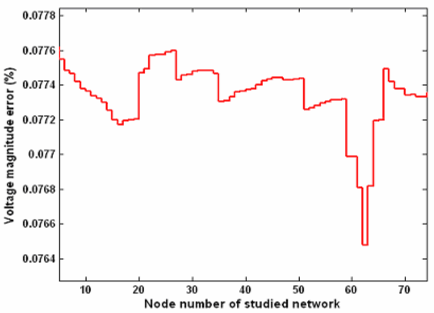

Figure 4. Voltage magnitude error for studied network with external reduction

Secondly, in order to validate the dynamic equivalent. Every DGs in distribution network are aggregated into a dynamic equivalent generator. The parameters of the coherent and aggregated generators for the equivalent feeder (TVPPx) are given in Table 1. The number of nodes in original network is 317 nodes while those of reduced network retained 15 nodes.

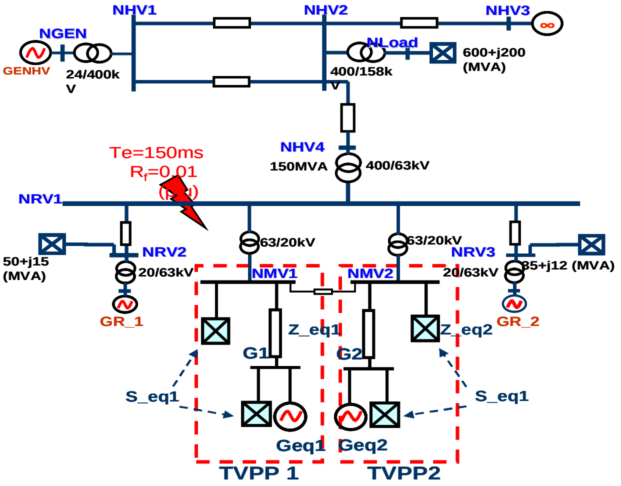

Figure 5. Constitution of TVPPs

Dynamic aggregated parameters						
	G1	G2	G3	G4	G5	**Geq1**
Sn (MVA)	1.2	3.53	5	3.53	5	18.26
Pn (MW)	1	2.85	4	2.85	4	14.7
Un (kV)	1.008	0.4	11	0.4	11	20
H (MWs/MVA)	0.56	1.5	1	1.5	1	1.116
Ra (pu)	0.0025	0.004	0.0024	0.004	0.0024	0.00284
Xi (pu)	0.13	0.13	0.0765	0.13	0.0765	0.09373
Xd (pu)	3.15	2.82	1.89	2.82	1.89	2.2376
X'd (pu)	0.24	0.215	0.193	0.215	0.193	0.20365
X"d (pu)	0.14	0.145	0.139	0.145	0.139	0.14127
T'do (pu)	2.35	3	2.35	3	2.35	2.62988
T"do (pu)	0.035	0.06	0.026	0.06	0.026	0.03020
Xq (pu)	3.15	1.6	1.478	1.6	1.478	1.57854
X'q (pu)	0.24	0.3	0.24	0.3	0.24	0.25993
X"q (pu)	0.14	0.195	0.15	0.195	0.15	0.16373
T'qo (pu)	2.35	1	2.35	1	2.35	2.31734
T"qo (pu)	0.035	0.03	0.042	0.03	0.042	0.04109

Table 1. Parameter of coherent and aggregated generators.

A three phases short-circuit in a MV network is supposed to observe the dynamic behaviors of studied network with and without equivalent.

Figure 6 presents the voltage behavior at busbar when the fault occurs. The results show that the behavior of original network and the reduced network are coincided.

The behavior of equivalent generator in comparison with the coherent generators can be seen in Figure 7.

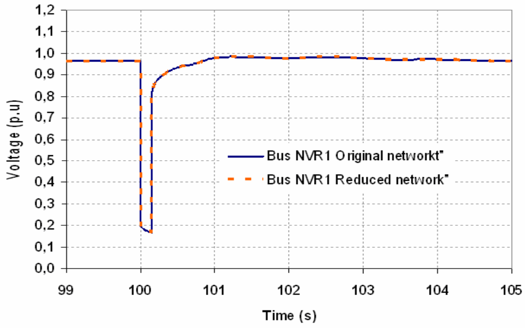

Figure 6. Comparison of voltage behavior at the short-circuit bus.

The result shows that the active power behavior of aggregated generator represent perfectly the group of DGs in distribution network.

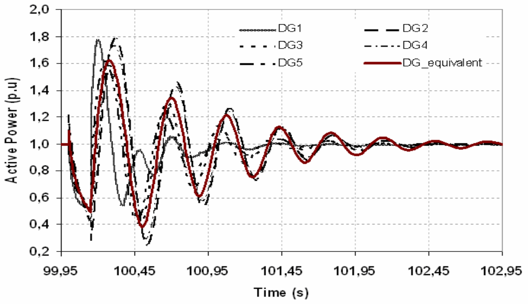

Figure 7. Comparison of active power behavior of the DGs group and its equivalent

IV. CONCLUSIONS

The hybrid methods to build the equivalent model which represent the large distribution network in presence distributed generators have been presented in the paper. This method allows DSO or TSO to control a significant amount of "active" distribution network via the local operator (distributed agent). The distributed agents might also easily fulfil their task of management of its studied network without knowing much detail about the further network.

The obtained results pointed out that the small DGs (range 1MVA to 12MVA) connected at the same feeders have the similar behaviours. However, in order to assure the best coherent between the generators in equivalent model, the smaller sub-network could be created.

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