Modelling of Active Distribution Networks for Power System Restoration Studies

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Abstract: This paper presents an aggregated model of Active Distribution Networks (ADNs) appropriate for power system restoration studies. The ADN considers aggregated loads and inverter based generation, such as wind and photovoltaic generation. The load model incorporates: i) time series data for consumption; ii) voltage and frequency dependency; iii) under frequency load shedding; iv) disconnection behavior; and v) cold load pick-up. The generation model considers: i) time series data for generation; ii) over frequency active power reduction; iii) disconnection; and iv) reconnection behavior. The ADN model covers dynamic phenomena in the time scale of tens of seconds up to several minutes with the focus on frequency dynamics. Moreover, the model was tested in several case studies and shows adequate dynamic behavior.

Keywords: Under frequency load shedding, blackout, cold load pick-up, black start, island operation, frequency control, dynamic equivalent, aggregation, inverter based generation.

1. INTRODUCTION

Recognizing that power system blackouts are likely to occur, it is prudent to consider the necessary measures that reduce their extent, intensity and duration (IEEE, 2014). One of the promising measures is the utilization of Active Distribution Networks (ADNs) to support the restoration process, bringing the power system from the blackout or emergency state back to the normal state, as shown in Fig. 1 (a). These ADNs host Inverter Based Generation (IBG), i.e., wind and PhotoVoltaic (PV) generation. However, the incorporation of IBG into the restoration process is challenging for system operators.

In practice, a negative load model is still used by system operators to represent IBG in power system stability studies (Lammert et al., 2017). On the other hand, different methods exist that describe the dynamic behavior of ADNs studying small disturbances (Maqbool et al., 2016) or large disturbances (Chaspierre et al., 2017). Nevertheless, for power system restoration studies IBG is usually neglected, which is shown by a comprehensive review given in (IEEE, 2014). Furthermore, recent work on restoration dynamics in Germany is focused on gas turbines (Erlich et al., 2012) or pumped-storage plants (Weber and Krüger, 2008) and does not consider ADNs. These facts highly motivate the work reported in this paper.

The new contribution of this paper is a detailed model that describes the dynamic behavior of an aggregated ADN suitable for power system restoration studies. In particular, the ADN model incorporates the aggregation of load and IBG, as depicted in Fig. 1 (b). The aggregated load model considers: i) time series data for consumption; ii) voltage and frequency dependency; iii) Under Frequency Load Shedding (UFLS); iv) disconnection behavior; and v) Cold Load Pick-Up (CLPU). The aggregated IBG model involves: i) time series data for generation; ii) over frequency active power reduction; iii) disconnection; and iv) reconnection behavior. The ADN model is adequate for power system restoration studies considering long-term dynamics in the time scale of tens of seconds up to several minutes with the focus on frequency dynamics. The model does not incorporate grid forming capabilities.

The remainder of the paper is organized as follows. Section 2 duly discusses the dynamic behavior of the aggregated load model. Section 3 presents the aggregated IBG model and its functions. Section 4 shows the case studies. Finally, the conclusions are drawn in Section 5.

![Fig. 1. (a) Power system states (ENTSO-E, 2015).](image)

(b) Aggregated model of the ADN.
2. LOAD MODEL

2.1 Overview

The load represents the aggregate consumption of the underlaying grids. The block diagram of the load model is depicted in Fig. 2 and the inputs are time series \((P_0, Q_0)\) and measurement \((V, f)\) signals. The outputs are active and reactive power \((P, Q)\) signals interfaced with the grid. Within the load model block various functions are implemented (see Sections 2.2–2.7).

2.2 Time series of consumption

If available, time series data of the consumption can be provided to the load model using the input signals for active and reactive power, \(P_0\) and \(Q_0\), respectively. As for some power system restoration studies the time scale of interest is several minutes or even hours, the consideration of time series data is important. A representative example using time series data for the consumption is shown in Fig. 3 from \(t = 0\) s to \(t = 500\) s (interval 1).

2.3 Voltage and frequency dependency

The voltage and frequency dependencies of the aggregated load are considered in the exponential load model according to (Van Cutsem and Vournas, 2008):

\[
P_{\text{exp}} = P_0 \left( \frac{V}{V_0} \right)^\alpha \cdot (1 + k_{pf} \cdot \Delta f) \tag{1}
\]

\[
Q_{\text{exp}} = Q_0 \left( \frac{V}{V_0} \right)^\beta \cdot (1 + k_{qf} \cdot \Delta f) \tag{2}
\]

where \(P_{\text{exp}}\) and \(Q_{\text{exp}}\) are the active and reactive power, respectively, consumed by the load at the bus voltage \(V\). \(P_0\) and \(Q_0\) are the active and reactive power, respectively, under the reference voltage \(V_0\), also referred to as the initial operating conditions. The exponents \(\alpha\) and \(\beta\) depend on the type of load. The parameters \(k_{pf}\) and \(k_{qf}\) describe the frequency dependency of the load. The parameter values for the voltage and frequency dependency are based on (Milanovic et al., 2013) and listed in Table 1. A typical example of load frequency dependency is shown in Fig. 3 from \(t = 500\) s to \(t = 833\) s (interval 2).

2.4 Under frequency load shedding

For cases with a major frequency drop in the system, an automatic UFLS scheme is an effective measure to prevent a further frequency decrease and a system collapse (ENTSO-E, 2015). As large frequency deviations can occur during the restoration process, the UFLS scheme might be considered for investigations. An algorithm for the implementation of the UFLS scheme is shown in Fig. 4. In (ENTSO-E, 2015), 6 load shedding steps are defined, which can be seen in line 2 of the algorithm. Starting from load shedding step 6, the reduced load demand \(P_{\text{UFLS}}\) is calculated in line 5, until \(n = 0\) is reached. The parameter values for the UFLS scheme are based on (ENTSO-E, 2015) and listed in Table 1. An illustrative example of the UFLS scheme is shown in Fig. 3 from \(t = 833\) s to \(t = 1133\) s (interval 3).

2.5 Disconnection

If the frequency further decreases and the UFLS scheme is not sufficient, the load is entirely disconnected from the network, which is usually done manually by the system operator. This disconnection function is implemented as:

\[
P_{\text{Load, disc}} = 0 \tag{3}
\]

where \(P_{\text{Load, disc}}\) is the active power demand of the load, which is set to zero when the frequency limit for the total load disconnection \(f_{\text{disc}}\) is reached. The disconnection settings for the aggregated load model consider the requirements for the UFLS scheme stated in (ENTSO-E, 2015) and are listed in Table 1. For the illustration of the load disconnection behavior, an example is depicted in Fig. 3 from \(t = 1333\) s to \(t = 1500\) s (interval 4).

1: procedure Under frequency load shedding
2: \(n := 6\)
3: repeat
4: if \(f < f_n\) then
5: \(P_{\text{UFLS}} := P_{\text{exp}} \cdot (1 - \sum_{i=1}^{n} P_i)\)
6: else
7: \(n := n - 1\)
8: endif
9: until \(n = 0\)
10: end procedure

Fig. 4. Algorithm for under frequency load shedding.
2.6 Cold load pick-up

If the load has been de-energized for several hours or more, the inrush current upon re-energizing the load can be significantly higher than in normal operation, which is called CLPU. The increased CLPU demand is due to: i) the magnetizing inrush currents of the system transformers; ii) the starting transients from induction motors; and iii) the loss of load diversity of process and thermostatically controlled loads (Schneider et al., 2016). As this phenomenon might influence the reconnection behavior of distribution feeders, it should be considered for the restoration process. The most common method of addressing the CLPU is the use of a CLPU curve:

\[ P_{\text{CLPU}} = P_{\text{exp}} \cdot \left(1 + a \cdot e^{-(t-t_0)/\tau}\right) \]

(4)

\[ Q_{\text{CLPU}} = Q_{\text{exp}} \cdot \left(1 + a \cdot e^{-(t-t_0)/\tau}\right) \]

(5)

where \(P_{\text{CLPU}}\) and \(Q_{\text{CLPU}}\) represent the active and reactive power consumption of the aggregated load during the CLPU event, and \(P_{\text{exp}}\) and \(Q_{\text{exp}}\) are the active and reactive power values from the exponential load model (see Section 2.3), respectively. The parameters \(a\) and \(\tau\) represent the peak value and time constant of the CLPU event, respectively, with \(t_0\) as the instant of reconnection. The parameter values for the CLPU are based on real measurement data from a German system operator and listed in Table 1. An example of the CLPU is shown in Fig. 3 from \(t = 1500\) s to \(t = 3000\) s (interval 5).

The different modes can be summarized in a state diagram as shown in Fig. 5 that consists of four states, i.e., Normal, UFLS, Disconnection and CLPU. To change from CLPU to Normal, \(P_{\text{CLPU}}\) is approximately \(P_{\text{exp}}\). For clarity reasons, only frequency requirements are depicted.

![State diagram of the load model.](image)

Table 1. Parameters of load and inverter based generation model

| Model | Mode | Description | Symbol | Value | Unit |
|-------|------|-------------|--------|-------|------|
| Load  | Voltage and frequency dependency | Active power voltage dependency | \(\alpha\) | 0.62 | [-] |
|       |       | Reactive power voltage dependency | \(\beta\) | 0.96 | [-] |
|       |       | Active power frequency dependency | \(k_{\text{pf}}\) | 1 | [%/Hz] |
|       |       | Reactive power frequency dependency | \(k_{\text{pq}}\) | 1 | [%/Hz] |
| Under frequency load shedding | Load shedding step 1 | \(f_1\) | 49.0 | [Hz] |
|       | Load shedding step 2 | \(f_2\) | 48.8 | [Hz] |
|       | Load shedding step 3 | \(f_3\) | 48.6 | [Hz] |
|       | Load shedding step 4 | \(f_4\) | 48.4 | [Hz] |
|       | Load shedding step 5 | \(f_5\) | 48.2 | [Hz] |
|       | Load shedding step 6 | \(f_6\) | 48.1 | [Hz] |
|       | Disconnected load (of \(P_0\)) step 1 | \(P_1\) | 5 | [%] |
|       | Disconnected load (of \(P_0\)) step 2 | \(P_2\) | 10 | [%] |
|       | Disconnected load (of \(P_0\)) step 3 | \(P_3\) | 10 | [%] |
|       | Disconnected load (of \(P_0\)) step 4 | \(P_4\) | 10 | [%] |
|       | Disconnected load (of \(P_0\)) step 5 | \(P_5\) | 10 | [%] |
|       | Disconnected load (of \(P_0\)) step 6 | \(P_6\) | 5 | [%] |
| Inverter based generation | Over frequency active power reduction | Gradient power reduction | \(m_{\text{load}}\) | 40 | [%/Hz] |
|       | High frequency limit power reduction | \(t_{\text{load}}\) | 50.2 | [Hz] |
|       | High frequency limit disconnection | \(f_{\text{max,dis}}\) | 51.5 | [Hz] |
|       | Low frequency limit disconnection | \(f_{\text{min,dis}}\) | 47.5 | [Hz] |
|       | High voltage limit disconnection | \(V_{\text{max,dis}}\) | 1.1 | [pu] |
|       | Low voltage limit disconnection | \(V_{\text{min,dis}}\) | 0.8 | [pu] |
|       | Gradient power reconnection | \(m_{\text{rec}}\) | 10 | [%/min] |
|       | High frequency limit reconnection | \(f_{\text{max,rec}}\) | 50.05 | [Hz] |
|       | Low frequency limit reconnection | \(f_{\text{min,rec}}\) | 47.5 | [Hz] |
|       | High voltage limit reconnection | \(V_{\text{max,rec}}\) | 1.1 | [pu] |
|       | Low voltage limit reconnection | \(V_{\text{min,rec}}\) | 0.85 | [pu] |
|       | Time duration reconnection | \(\Delta t_{\text{min,rec}}\) | 60 | [s] |

\(^\wedge\) Needs to be adjusted with the under frequency load shedding scheme.
3. INVERTER BASED GENERATION MODEL

3.1 Overview

The IBG represents an aggregated generation including the underlying grids. The IBG model is based on the small-scale (distribution-connected) Western Electricity Coordinating Council (WECC) model for PV systems (WECC, 2012) and is extended with additional functions required for the restoration process. The block diagram of the IBG model is shown in Fig. 6 and the inputs of the electrical control block are time series ($P_m$) and measurement ($V, f$) signals. The outputs are current command ($I_{dcmd}, I_{qcmd}$) signals. From the inverter block the current ($I_d, I_q$) signals are interfaced with the grid. Within the electrical control block various control modes are included (see Sections 3.2-3.6).

3.2 Time series of generation

Similar to the load model, time series data for the generation can be considered for the IBG model using the input signal for the available active power $P_m$. As the primary energy source of PV or wind generation varies, sudden changes of active power output might interfere with the restoration process. Therefore, if time series data of generation is available, it should be considered for power system restoration studies. An example using time series data for the generation is illustrated in Fig. 7 from $t = 0$ s to $t = 500$ s (interval 1).

3.3 Over frequency active power reduction

Over frequency active power reduction (also known as $P(f)$ control) is required for IBG in order to counteract over frequencies in the system. The reduced active power output $P_{red}$ of the IBG model is defined as:

$$P_{red}(f) = P_{freeze} \cdot (1 - m_{red} \cdot (f - f_{red}))$$

where $P_{freeze}$ is the saved active power value when exceeding the frequency limit for power reduction $f_{red}$. The parameter $m_{red}$ is the active power reduction gradient. The parameter values for the over frequency active power reduction are based on (VDE, 2011) and listed in Table 1. An example of $P(f)$ control of IBG is depicted in Fig. 7 from $t = 555$ s to $t = 875$ s (interval 2).

3.4 Disconnection

If frequency or voltage limits are violated, the IBG disconnects from the grid due to tripping of the protection system (delay times are neglected). The disconnection behavior of the IBG model is defined as:

$$P_{IBG, disc} = 0$$

where $P_{IBG, disc}$ denotes the active power output of the IBG model, which is set to zero when limits are exceeded. The parameter values for the voltage and frequency disconnection settings of IBG are based on (VDE, 2011) and listed in Table 1. For the illustration of the IBG disconnection behavior, an example is depicted in Fig. 7 from $t = 875$ s to $t = 1060$ s (interval 3).

Fig. 6. Block diagram of the IBG model.

Fig. 7. IBG behavior during frequency deviations.

3.5 Reconnection

The reconnection behavior of IBG is seen in the algorithm of Fig. 8. Before IBG is allowed to reconnect, grid frequency $f$ has to be within defined limits (normal operating range) for a duration of $\Delta t_{\text{min,rec}}$ seconds, as seen in line 2 of the algorithm. When the reconnection condition is fulfilled, two different methods can be distinguished that are usually used for the reconnection behavior (VDE, 2011): i) immediate reconnection with full available power $P_m$ (step) as seen in line 4; or ii) slow linear increase of power starting at time instant $t_{\text{rec}}$ until available power $P_m$ is reached (ramp) as seen in line 6. For clarity reasons, only frequency reconnection requirements are illustrated in the algorithm of Fig. 8. The parameter values for the ramp reconnection behavior of IBG are based on (VDE, 2011) and listed in Table 1. An example is shown in Fig. 7 from $t = 1060$ s to $t = 1660$ s (interval 4).

1: procedure Reconnection
2: if $f_{\text{min,rec}} < f(t) < f_{\text{max,rec}}$ for $\Delta t_{\text{min,rec}}$ then
3: if step then
4: $P_{\text{rec}}(t) := P_m(t)$
5: else ramp
6: $P_{\text{rec}}(t) := P_m(t) \cdot m_{\text{rec}} \cdot (t - t_{\text{rec}})$
7: until $P_{\text{rec}}(t) = P_m(t)$
8: else
9: $P_{\text{rec}}(t) := P_{\text{disc}}$
10: end procedure

Fig. 8. Algorithm for the reconnection of IBG.
The different IBG control modes can be summarized in a state diagram as seen in Fig. 9 that consists of the states Normal, Reduction, Disconnection and Reconnection. For clarity reasons, only frequency requirements are depicted in the diagram. If, for instance, an over frequency event occurs during the reconnection process, the state is changed from Reconnection to Reduction. The transition between these two states is illustrated in detail in Fig. 10. As soon as the frequency falls below the threshold \( f_{\text{red}} \) at \( t = 1436 \text{ s} \), the reconnection process is continued until \( P_{\text{rec}} = P_{\text{m}} \) and the Normal state is reached.

Fig. 9. State diagram of the IBG model.

4. CASE STUDIES

4.1 Overview

The reported ADN model has been used in various power system restoration studies that are presented briefly in Sections 4.2–4.5. An overview of the studies and the used functions of the load and IBG model is given in Table 2.

4.2 Case 1

In this study the ADN model is investigated on a simple test system as shown in Fig. 1 (b). The dynamic behavior of the combination of load and IBG was analyzed under a given frequency deviation, as seen in Fig. 11. From \( t = 0 \text{ s} \) to \( t = 1000 \text{ s} \), the frequency dependency of the load and the over frequency active power reduction of the IBG lead to a significant change in the residual load seen by the system operator. At \( t = 1000 \text{ s} \) the UFLS starts acting until half of the load is disconnected. At this time, the generation is higher than the consumption, which results in a slightly negative residual load. After reconnecting the ADN at \( t = 1500 \text{ s} \), the residual load is dominated by the CLPU phenomenon and the reconnection ramp of IBG.

![Fig. 10. Over frequency active power reduction during reconnection of IBG.](image-url)

![Fig. 11. Load and IBG behavior during frequency deviations.](image-url)

| Model | Mode | Case |
|-------|------|------|
| Load  | Voltage and frequency dependency | ✓ | ✓ | ✓ | ✓ |
|       | Under frequency load shedding | ✓ | ✓ | ✓ | ✓ |
|       | Cold load pick-up | ✓ | ✓ | ✓ | ✓ |
| IBG   | Over frequency active power reduction | ✓ | ✓ | ✓ | ✓ |
|       | Disconnection | ✓ | ✓ | ✓ | ✓ |
|       | Reconnection | ✓ | ✓ | ✓ | ✓ |
In this study the ADN model was used to analyze the impact of over frequency active power reduction of IBG on power system restoration and the details can be found in (Hachmann et al., 2017). The $P(f)$ control is particularly relevant for the operation of small islands within the distribution system. The results of this study reveal that using the full potential of IBG active power reduction, leads to improved frequency dynamics in small island grids without any impact on the overall system behavior in normal operation.

4.3 Case 2

In this study the ADN model was used to analyze the impact of over frequency active power reduction of IBG on power system restoration and the details can be found in (Hachmann et al., 2017). The results of this study reveal that using the full potential of IBG active power reduction, leads to improved frequency dynamics in small island grids without any impact on the overall system behavior in normal operation.

4.4 Case 3

In this study the ADN model was used to analyze the impact of over frequency active power reduction of IBG on power system restoration and the details can be found in (Hachmann et al., 2017). The results of this study reveal that using the full potential of IBG active power reduction, leads to improved frequency dynamics in small island grids without any impact on the overall system behavior in normal operation.

4.5 Case 4

In this study the ADN model was used to analyze the impact of over frequency active power reduction of IBG on power system restoration and the details can be found in (Hachmann et al., 2017). The results of this study reveal that using the full potential of IBG active power reduction, leads to improved frequency dynamics in small island grids without any impact on the overall system behavior in normal operation.

5. CONCLUSIONS

This paper presents a detailed model of an aggregated ADN that is adequate for power system restoration studies in the time scale of tens of seconds up to several minutes. The model was developed with the focus on frequency dynamics and control. It includes a combination of aggregated load and IBG. The load model involves: i) time series data for consumption; ii) voltage and frequency dependency (i.e. exponential load model); iii) UFLS; iv) disconnection behavior; and v) CLPU. On the other hand, the aggregated IBG model considers: i) time series data for generation; ii) over frequency active power reduction; iii) disconnection; and iv) reconnection behavior. The ADN model was successfully applied in several case studies with real grid data and shows adequate dynamic behavior. Moreover, the studies reveal that the consideration of ADNs can support the power system restoration process. Finally, the developed ADN model helps system operators to incorporate IBG into their restoration schemes.

Future work will also consider the frequency sensitive mode of IBG (i.e. providing primary frequency response). Furthermore, additional voltage control functions of IBG, such as fault ride-through and dynamic voltage support and quasi-stationary voltage control by means of reactive power (i.e. $Q(V)$ control), are of interest.

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