The white paper demonstrates the feasibility of industrial microgrids by modeling an actual industrial network with on-site distributed generation to temporarily keep crucial consumers in operation in islanded mode, and to increase reliability in the case of blackouts.

The objective of this white paper was to determine the requirements for safe and reliable operation of a microgrid within an existing industrial network which is connected to the public grid and which can also function in islanded operation. To do this a typical industrial 20/0.4 kV grid model was constructed in a network planning tool. Various generators, such as those for biomass, diesel and gas, their controllers, and consumers were modeled in order to study dynamic stability. Furthermore, the existing protection system was analyzed within the simulation model. In addition to a variety of load flow and time domain simulations, a fault analysis was also conducted to verify the reliability and the stability of the microgrid. Advanced control strategies have been developed together with a comprehensive protection system to allow both grid connected operation and islanded operation.

I. Introduction

Reliability of the electric power system has become one of the major concerns and it is a current topic across the industry. In the event of a major blackout of the public power grid, for example as a result of severe weather, customers may have to wait for days before being reconnected to the power grid. With the growing integration of distributed generation (DG) into the grid, a reliable supply of power has become a concern, but it should be mentioned that this also offers new opportunities. When locally connected, DG can form microgrids (MG) (see Fig. 1) to provide a reliable solution by supplying critical loads during blackouts. The design, implementation and investigation of such MGs is the main focus of this paper.

Industries operating with crucial loads cannot afford a power interruption in the form of an extensive blackout, which may lead to significant technical problems and financial losses. Many industries operate DG units, in order to benefit from the premiums paid according to the "Renewable Energy Sources (RES) Act". Implementation of a grid connected MG with an existing RES-based DG is an attractive solution for such industries.

In spite of the aforementioned advantages, islanded MG operation may be prevented due to several reasons listed in [2]:

1. Fault contribution from DG may not be sufficient to allow satisfactory operation of protection systems
2. DG may not be able to regulate the voltage and frequency within the islanded system
3. The parallel operation of DG units within the island may cause problems
4. Unsynchronized, out-of-phase reclosing may occur when the islanded distribution is reconnected to the distribution system
5. The IEEE 1547.2-2008 standard requires all utilities, operating DG units to detect grid problems and to subsequently disconnect the DG units from the grid within a maximum of 2 seconds [3]
Therefore, it is essential to analyze whether it is possible to overcome the above mentioned hurdles to ensure safe and reliable operation of the MG. An existing industrial grid comprised of RES-based DG units was modelled in order to study the feasibility of MG solutions for industries with existing DG units that depend on a reliable power supply, even in the case of a blackout. Dynamic modelling of a single biomass plant along with gas and diesel generators and associated controls was carried out. Static and dynamic loads were modelled to investigate the impact of load switching on grid voltage and frequency. Installed protection systems were analyzed and necessary improvements were proposed. In addition, blackout detection and transition schemes to go from grid connected mode to islanded mode and vice versa were developed. The steady state stability as well as load step and fault clearing capabilities of the modelled MG were evaluated by conducting fault, load flow and time-domain simulations. Finally, a comparison was drawn between MG operation with either a biomass plant or gas generators being activated.

II. Description of the modelled microgrid

A. Modelled grid

The modelled microgrid shown in Fig. 2 consisted of an onsite medium voltage (MV) network with several low voltage (LV) feeders and a connection to the public grid on the MV level. The LV grid represented a typical industrial grid with industrial loads and renewable DG units. The minimum and peak loads in the MG were 100 kVA and 1000 kVA respectively, whereas the total power generation varied from 350 kVA to 6000 kVA depending on the DG units that were active in the MG. All motor loads were equipped with soft starters to limit the starting current absorbed by the motors. The generators’ attributes are summarized in Table 1.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Rated voltage (kV)</th>
<th>Apparent power (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>6.3</td>
<td>4000</td>
</tr>
<tr>
<td>Gas generator 1, 2</td>
<td>0.4</td>
<td>450</td>
</tr>
<tr>
<td>Backup diesel generator</td>
<td>0.4</td>
<td>375</td>
</tr>
</tbody>
</table>

B. Dynamic model of the biomass power plant

Although there are several methods of utilizing biomass, the most common CHP configuration in use today is direct firing of solid biomass in a boiler to create high-pressure steam. The steam generated in the boiler is used to power a steam turbine, which in turn drives a synchronous generator. Several components are required to model the capability of the biomass plant to respond to load changes. The modelled components are listed below:

I. Boiler and boiler control characteristics
II. Fuel dynamics
III. Turbine and power/speed control characteristics
IV. Automatic voltage control (AVC)
V. Electronic speed governor (ESG)

The biomass plant is operated in boiler following mode, in which the power output of the biomass plant is controlled by the turbine controls while the boiler controls regulate the flow of fuel into the combustion chamber in order to maintain constant steam pressure. The modelled biomass plant is illustrated in Fig. 3.

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Fig. 2: Schematic of the modelled microgrid with 20/0.4 kV network and various DG units and loads
The speed governor is responsible for controlling frequency, whereas the automatic voltage control regulates voltage at the generator terminals. Active and reactive power control ensures that active and reactive power is shared equally between the generators.

The standard turbine-governor model TGOV5 shown in [4] was modified to simulate the dynamic behavior of the biomass plant. The dynamic response of the boiler depends on the combustion characteristics of biomass fuels. The combustion characteristics of biomass fuels, which are shown in [5], were modelled using the transfer function shown in (1).

\[ G(s) = \frac{\text{Heat release}}{\text{Fuel flow}} = \frac{e^{-20s}}{1 + 60s} \]  

A non-reheat steam turbine was modelled using the transfer function shown in (2).

\[ G(s) = \frac{1}{1 + st_{cu}} \]  

The turbine and boiler controls were tuned using the Ziegler-Nichols closed-loop method.

C. Dynamic modelling of diesel and gas generators

Diego and gas generators are widely used for power generation because they are able to start quickly, provide good load following capabilities and they are very reliable. The dynamic response of a diesel engine varies from that of a gas engine due to different combustion processes. Consequently, gas generators are not able to accept sudden load changes as quickly as diesel engines respond.

Gas generators

The dynamic response of gas engines varies depending upon the fuel, fuel-air mixture and design. Thus, it is important to systematically characterize the dynamic responses of gas generators into different classes. The IS/ISO 8528-5 standard characterizes the dynamic response of gas engines into 4 classes, namely G1 to G4, whereby G3 has the fastest dynamic response and G4 lets the customer and the manufacturer determine the requirements [6]. For this work the parameters were tuned in such a way that:

I. for a step load increase of 30% of the rated load, the frequency does not drop below 47.5Hz

II. and simultaneously for a 100% load rejection, the frequency does not exceed 55Hz

The recovery times ensure that the system returns to the steady state frequency within the prescribed time, according to the IS/ISO 8528-5 standard.

An existing model known as the Woodward diesel governor model (DEGOV1) has been utilized in several power system studies to model gas and diesel generators [7] [8] [9]. The DEGOV1 model, which is available in the PowerFactory library, was modified in order to model two 450 kVA gas generators. The DEGOV1 model consists of the following components:

1. ESG (electronic speed governor)
2. Fuel injection system (FIS) & engine
3. AVC

The gas generator and its associated controls are shown in Fig. 4.

The ESG ensures that power output follows the set point determined by the active power controller. Additionally, it regulates the MG frequency isochronously in islanded mode by controlling the output power. The output of the speed governor is sent to an actuator, which controls the FIS. The FIS then injects the air-fuel mixture into the engine, which then produces torque on the crankshaft according to the 4 stroke engine principle, which multiplied by the speed of the engine equals the mechanical output power \(P_{\text{mech}}\). The synchronous generator then converts the mechanical power into electrical power. The AVC regulates the terminal voltage.

Diesel generators

Due to the similarities between diesel and gas generators, DEGOV1 can also be used to model diesel generators. In order to achieve accurate results a 375 kVA diesel generator, as modelled in [10], was implemented in PowerFactory. This diesel generator model is based on actual field measurements.
D. MG Controller

The MG controller (MGC), shown in Fig. 5, is responsible for the system dispatch, such as generator start/stop and feeder protection coordination, as well as power balancing between generators and consumers, together with the necessary data logging and acquisition. MGC capabilities can be enhanced to perform additional tasks such as under frequency load shedding and demand side management.

![Microgrid control diagram](image)

Fig. 5. Microgrid control diagram

The control structure for the MG concept is depicted in Fig. 6. The microgrid control (MGC) logic determines power set points, start/stop instructions etc. for the generator controls and receives actual power measurements for each connected generating unit. The generator control and monitoring system (generator CMS), in turn, regulates the output power of the connected generator by communicating with the generator’s primary controls. The primary controls at the generator level ensure voltage and frequency stability.

![Control structure and controller coordination](image)

Fig. 6. Control structure and controller coordination

E. Load modelling

In order to simulate the dynamic behavior of the MG, dynamic and static loads were modelled. Dynamic loads are time-dependent and their active and reactive power depends on the actual voltage and frequency over time. In contrast, static loads are time-invariant and their active and reactive power depends only on voltage and frequency at that instant in time. The voltage and frequency dependency of the active and reactive power absorbed by a static load is demonstrated in (3).

\[
P = P_S \cdot \left( \frac{V}{V_S} \right)^{1.6} \quad \text{and} \quad Q = Q \cdot \left( \frac{V}{V_S} \right)^{1.8}
\]

Motors and pumps are categorized as dynamic loads, since they require much higher starting currents in comparison to the steady state operation. Soft starters were used to limit their starting currents for all motors, pumps and compressors in the MG.
III. Protection systems and schemes

Protection devices are installed in an electric power system in order to protect both humans and the equipment. Their task is to disconnect faulty or overloaded equipment, or parts of the system, in order to prevent damage. The introduction of DG units can have a significant impact on power flow, voltage stability and grid protection systems. Since traditional distribution networks are radial, meaning that power flows in only one direction i.e. from the grid to consumers, the protection scheme is relatively simple and consists mainly of overcurrent (OC) protection. Introducing DG units into the network means that unidirectional power flow can no longer be guaranteed, and hence a simple OC protection scheme is longer sufficient. Typical problems that may occur are:

1. Blinding of protection: In the case of a DG unit connected to the distribution grid, the fault current detected by OC protection at the feeder may be reduced, due to the contribution of the DG unit to the total fault current, and this may prevent the OC relay from functioning.

2. False tripping: This occurs when a generator which is installed on a feeder, contributes to the fault current in an adjacent feeder connected to the same substation. The generator contribution to the fault current can exceed the pick-up level of the OC protection which can lead to a trip of the healthy feeder before the actual fault is cleared [11].

The protection systems which were implemented to ensure safe and reliable operation are described below.

A. Generator protection

An underfrequency/overfrequency relay was implemented for the steam turbine (see settings in table 2). Overload protection was modelled using a time inverse OC relay with an “ANSI/IEEE extremely inverse” characteristic (see table 3 for settings) for gas and diesel generators.

Table 2: Maximum operating time of a steam turbine at full load [12]

<table>
<thead>
<tr>
<th>Frequency at full load [Hz]</th>
<th>Maximum operating time [sec]</th>
<th>Frequency at full load [Hz]</th>
<th>Maximum operating time [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>0</td>
<td>48.5</td>
<td>600</td>
</tr>
<tr>
<td>50</td>
<td>Continuously</td>
<td>48</td>
<td>60</td>
</tr>
<tr>
<td>49</td>
<td>6000</td>
<td>47.5</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3: Overload protection settings for diesel and gas generators

<table>
<thead>
<tr>
<th>Generator</th>
<th>Rated current [A]</th>
<th>1.1 x Rated current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>541</td>
<td>595</td>
</tr>
<tr>
<td>Gas</td>
<td>650</td>
<td>715</td>
</tr>
</tbody>
</table>

B. Load protection

Fuses were modelled to protect the loads against overloading and short circuits. MV fuses were implemented to provide a backup for the OC protection. The fuses and OC protection were coordinated to provide selective fault clearing.

C. Directional protection coordination for bidirectional power flow

Due to the bidirectional flow of power, it was necessary to implement directional protection relays (DLR) where gas and diesel generators are connected to the central busbar (C_BB) (see Fig. 8) to solve the issue of false tripping.

IV. Microgrid stability study

Load flow and time domain simulations were performed to examine power system stability and the functional reliability of the MG in the various operating modes mentioned below:

1. Grid connected mode with all DGs operating in parallel
2. Separation of the MG in the case of a blackout
3. Black-start with a backup diesel generator supplying crucial loads
4. Islanded mode with gas generators supplying all of the MG loads
5. Island mode with biomass plant supplying all the MG loads
6. Resynchronization of the MG with the public MV grid
A. Load flow simulations
Load flow simulations were conducted for islanded mode as well as grid connected mode in order to ensure the stability of steady state voltage as well as to ensure that electrical equipment such as transformers, circuit breakers (CB) and cables were not overloaded.

Depending on the operating mode, respective generators were switched on to evaluate voltage stability at low loads and rated loads.

The results demonstrate that loading of transformers and cables did not exceed the designed loading limits. Voltage deviations at the MV and LV busbars did not exceed the permissible voltage deviation limits, according to the standard norms defined in [13].

B. Time domain simulations
Appropriate functioning of the MG in the above mentioned operating modes was evaluated by varying and switching loads, as well as by simulating short circuits. Parallel operation of DGs and correct load sharing between them was verified.

1) Grid connected mode and blackout
During normal operation all generators, except for the backup diesel generator, feed power into the grid based on the power set point. As expected switching loads did not endanger voltage or frequency stability, and short circuits were cleared reliably and selectively due to the large short circuit power from the MV grid.

2) Blackout
A low voltage/frequency condition was simulated (Fig. 9) to demonstrate separation of the MG from the MV grid. The frequency drop at E1 causes the CB, which interconnects the MG and the MV grid, to open at P1, which then activates the generator's over speed protection at P2, forcing it to shut down.

3) Black start with backup diesel generator
The backup diesel generator was utilized to perform a black start. Crucial loads connected to the emergency busbar (E_BB) and the gas compressors were switched on sequentially in order to avoid frequency and voltage swings. Gas compressors were switched on to allow MG operation with gas generators, which are required to meet the load requirements of the industrial grid. The results demonstrate that frequency and voltage stability are not endangered since the backup diesel generator offers good load step capability.

4) Islanded mode with gas generators
The gas compressors which were started previously by the diesel generator, allow the gas generators to be started and synchronized with the MG. Following synchronization, the backup diesel generator is shut down once again. The reconnection of loads is demonstrated in Fig. 10, shows the soft

starting of a 42kW pump at E1, and the switching of a 27kW load at E2, as well as a steady increase in static loads from 27kW to 135kW, starting at E3, over a period of 10 seconds.

5) Islanded mode with a biomass plant supplying all the MG loads
Starting-up a biomass plant requires a high level of power for auxiliary processes, and this is provided by the gas generators. Following start-up, the process of synchronizing the biomass plant with the MG is started at E1 (see Fig. 11). After successful synchronization with the MG at P1, the complete load provided by the gas generators is slowly taken over by the biomass plant. At E2 the gas generators are shut down after the load has been completely shifted to the biomass plant, which can now provide the entire load by itself.

6) Reconnecting the MG to the public MV grid
In order to reconnect to the MV grid, the MG must first be synchronized to the MV grid. The control methodology of all DGs must be immediately changed to power set point operation at the time of reconnection. Reconnection of the biomass plant to the MV grid is shown in Fig. 12. The reconnection process is started by activating the synchronization sequence at E1. The biomass plant is then synchronized with the MV grid at P1 and subsequently the biomass plant is switched to set point operation at P2. Changing to set point operation leads to an increase in the power produced by the biomass plant due to an active power set point of 3.1 MW.
C. A comparison between the load step and fault clearing capabilities of the biomass plant and the gas generators

The biomass plant or alternatively the gas generators may be operated in islanded mode to fulfill the load requirements of the analyzed industrial grid. The relatively small gas generator (450 kVA) would operate close to its rated power, whereas the larger biomass plant (4000 kVA) would have to operate close to its minimum load. It is important to evaluate the optimum mode of operation for the MG, and therefore the load step and fault clearing capabilities of the biomass plant and gas generators was compared. The test shown in Fig. 13, demonstrates a load increase and a load decrease of 150 kVA at E1 and E2 respectively. E3 and E4 represent 3 phase faults located at a static 80 kVA load and a 40 kVA pump respectively.

Fig. 13. Load step and fault clearing capabilities of gas generators and biomass plant

It is evident from Fig. 13 that the larger generation capacity of the biomass plant, even with its slower dynamics, enables it to compensate for greater load changes when compared to the highly dynamic but relatively small gas generator, which demonstrates larger deviations. Parallel operation of the gas generators would compensate for the large deviations.

V. Conclusions

This paper demonstrates the feasibility of an industrial site being operated as a microgrid (MG) for temporarily supplying autonomous electrical power in the event of an extensive blackout. Amongst other things the industrial site is comprised of several distributed generation units, such as diesel backup generators, gas generators and a biomass plant. Various technical issues related to the operation and control of a microgrid were identified. As described previously in this document, analyzing an MG solution required modelling several electrical components and controls. Several conclusions were drawn from the study. Diesel generators demonstrate the best step load capability. In this case it is slightly better than the response observed in the gas generators. Control of the biomass plant is relatively slow but was shown to be suitable for MG operation when it is loaded with a relatively constant power. Gas generators or a biomass plant are not suitable for black starting an MG since they require relatively high auxiliary power levels for start-up. Hence, diesel generation is most suitable for a black start, considering that there is no storage system available. Simulations demonstrated that the two gas generators (450 kVA each) and the biomass plant (4000 kVA) are both able to fulfill load requirements. In order to determine the optimal generation setup, the two were compared and this comparison demonstrated that gas generators require shorter starting times and possess faster voltage and frequency regulation compared to a biomass plant. In contrast, the larger biomass plant offers better fault clearing capabilities and therefore it is able to trip conventional overcurrent protection reliably and selectively. Nevertheless, integrating new protection systems into the MG can help to overcome the disadvantages associated with both technologies and hence it can lead to a substantial reduction in protection issues. The implementation of undervoltage/frequency monitoring was found to be necessary for blackout detection.

A further analysis demonstrated that modified generator controls, along with the implementation of a microgrid controller are able to fulfill the requirements related to system control and monitoring, and especially frequency and voltage stabilities, as well as to balance active and reactive power while operating in and transitioning between microgrid operating modes.

This study demonstrates the measures which are necessary to perform a black start and operate an existing industrial MG in a safe manner when there is a disconnection from public grid. The study shows that it is necessary to install a microgrid controller, interfacing major power producers.

The MG solution proposed here can be modified to allow for MG operation in other industrial networks. It is important to note that modifications would be required as industrial networks may differ substantially from each other.

Apart from that only minor technical changes, such as clearly defined operating strategies and instructions are required to operate the MG during an extensive black out of the public power grid.

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VII. REFERENCES


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