Microgeneration, Energy Storage, Power Converters and the regulation of voltage and frequency in the Low Voltage Grid

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Abstract— This paper focuses on the study and development of a system composed by Microgeneration (MG) and energy storage (ES), which together with other similar systems, might avoid over-and undervoltages, as well as mitigate voltage dips. The system may use the stored energy on deferred. These systems are expected to contribute to the regulation of the voltage and frequency of a low voltage grid, especially in the case of an isolated grid.

The increase of distributed generation, using mainly renewable energy sources (RES), motivated some technical and operational issues that have to be approached. Despite all the benefits of distributed generation and renewable energy, the intermittent character of such type of source and the mismatch between supply and demand might lead to some problems in reliability and stability of the grid, and to an inefficient use of RES.

The integration of energy storage systems (ESS) together with MG can help to achieve a better integration of RES, contributing to the reliability and stability of the grid. Besides that, the decentralized action of these systems can help adjust the voltage and frequency, contributing to the improvement of the electric power quality when the values go beyond the limits imposed by the norm NP EN 50160.

The model of a system composed by Microgeneration and energy storage was developed using the Matlab/Simulink software, as well as one rural low voltage grid. The capacity of these systems to regulate voltage and frequency was simulated, analyzing the values of active and reactive power, the voltage level profile, as well as the frequency.

Index Terms— Distributed generation, Microgeneration, Energy Storage, Electric Power Quality, Frequency and Voltage Regulation

I. INTRODUCTION

The economic and social development in many developed and developing countries is contributing to the growth of energy consumption in those countries. It is expected that this tendency remains for the next decades, although efforts are being made to improve energy efficiency [1]. According to [2], it is expected a 40% increase in world energy consumption by 2040 in comparison to 2012.

Almost 75% of the energy consumed nowadays is obtained through fossil fuels [3]. However due to economic and environmental issues, the interest in renewable energy has increased in the last years. There have been many agreements in order to reduce the emission of greenhouse gases, focusing on the other hand on sustainable energy and energy efficiency (e.g Kyoto Protocol or EU2020 [1]).

Many countries offered big incentives for renewable energy generation. Consequently MG, most of the times using RES, has become increasingly popular and distributed generation (DG) is part of the electrical grid nowadays. However despite all benefits of DG (economical, environmental, reduce of losses etc.), it motivates some technical issues and contributes to the deterioration of electric power quality. The electric power system changed a lot with the introduction of DG, which consequently leads to a new paradigm with bidirectional power flow.

The use of ESS in parallel with Microgeneration can help to mitigate some electric power quality issues and even improve the integration of RES into the grid [4]. These systems might be beneficial for the consumers and for the grid operator. According to the recently approved decree law in 2014 by the Portuguese government [5] (Decreto-Lei no 153/2014) the produced energy through MG should serve the effective necessities of the installation to which it is associated. An ESS installed in parallel to the MG is therefore highly benefic to the consumers. For example, in case of photovoltaic energy there is a huge mismatch between supply and demand [6]. Besides all benefits for the consumer, these systems can also be very advantageous to the grid operator [6], one of them being the improvement of electric power quality. This way, the impact of MG systems into the grid might be reduced, meaning that through the decentralized action of several of those systems the voltage and frequency of the grid could be regulated.

Considering the above, it is intended this way through MG and ES systems to avoid overvoltages and undervoltages, as well as to mitigate voltage dips. These systems are expected to contribute to the regulation of voltage and frequency of a low voltage grid, especially in the case of an isolated grid.

II. MODEL OF THE LOW VOLTAGE GRID

A rural low voltage grid was modeled using the software Matlab/Simulink in order to study the impact of the MG with ES systems on it. The main goal was to replicate a typical rural grid and therefore all components of the grid (Medium Voltage (MV) to Low Voltage (LV) Transformer, Electrical Lines and
Loads) were scoped according to the rules of low voltage grid installations [7], as elaborated in [8].

The rated value of the voltage in the MV part of the grid is 30kV, while in the LV part this value is 400V (line voltage). The connection of the medium to the low voltage is made by a 630kVA transformer.

Due to computational reasons, each load of the first branch is not represented by an equivalent load, each load factor is assumed to be 0.75, while the other branches receive 100kVA each.

As it can be seen in Fig. 1 there are four branches in the LV part of the grid. The first branch (R1), which will be the focus of this paper, represents a collection of households, while the second (RR1) and third branches (RR2) are some other rural grid networks. The fourth branch characterizes a local network (RL). The power assigned to the first branch is 200kVA as well as to the RR1 rural network, while the other branches receive 100kVA each.

Due to computational reasons, each load of the first branch represents a group of houses. In total there are 40 singular households, distributed by each one of the 8 equivalent loads. Each household consumption is assumed to be 6,9kVA [7]. The transmission of electrical energy is made by overhead power lines and the distance between the last equivalent load and the substation is 514m, which is a reasonable value for this topology of grid.

Some systems, composed of MG and ES, are also placed in the modeled grid, and they represent some of the structures placed in consumer households. Like the equivalent loads, these groups might represent more than one MG with ES system, depending on the number of systems attributed to each household.

A. Distribution network sizing

The dimensioning of all electric cables was made, considering the power consumed in each branch of the low voltage network. As mentioned before, all loads pictured in Fig. 1 represent a group of houses. However, not all houses consume maximum power simultaneously. Therefore in order to proceed to the sizing of the cables, the power of such loads was multiplied by a factor that stands for the simultaneous maximum demand of many houses (diversity factor), downstream the point that is considered. The value of this factor C, can be seen in the following table considering N, the number of houses:

<table>
<thead>
<tr>
<th>Branch</th>
<th>Installed power [kVA]</th>
<th>Load Factor</th>
<th>Actual power supply required (3 phase) [kVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – RR1</td>
<td>200</td>
<td>0.75</td>
<td>150</td>
</tr>
<tr>
<td>3 - RR2</td>
<td>100</td>
<td>0.75</td>
<td>75</td>
</tr>
<tr>
<td>4 - RL</td>
<td>100</td>
<td>0.75</td>
<td>75</td>
</tr>
</tbody>
</table>

The power to be consumed by the 4 branches should be 437.6kVA which corresponds to a high load scenario. In order to size the electric lines, the power flowing in each line has to be taken into consideration. The current might be calculated using equation (1), being S the apparent power supply required and U_n the nominal voltage:

\[ I_s = \frac{S}{\sqrt{3} U_n} \]  

Hence, the maximum current transported in each branch can be calculated. The results are shown in Table IV:
Keeping in mind that the maximum voltage drop in a LV network branch defined by the Portuguese distribution operator EDP is 8%, the following type of overhead power lines was chosen [7]:

<table>
<thead>
<tr>
<th>Section (mm²)</th>
<th>R₀ (Ω/km)</th>
<th>X (Ω/km)</th>
<th>Z (Ω/km)</th>
<th>Iₓ (A)</th>
<th>Iₓ=Iᵧ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LXS 4x70</td>
<td>0,443</td>
<td>0,100</td>
<td>0,535</td>
<td>190</td>
<td>160</td>
</tr>
<tr>
<td>LXS 4x95</td>
<td>0,320</td>
<td>0,100</td>
<td>0,397</td>
<td>230</td>
<td>200</td>
</tr>
</tbody>
</table>

In a LV distribution network, loads are usually single phased, which leads to unbalances in the three-phase power system. Thus, the distribution of power per phase in every load of R1 is the following:

<table>
<thead>
<tr>
<th>Load</th>
<th>Phase</th>
<th>R [%]</th>
<th>S [%]</th>
<th>T [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>70</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>10</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>35</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>60</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>60</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>20</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>15</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>50</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>R1</td>
<td>40</td>
<td>30,625</td>
<td>29,375</td>
</tr>
</tbody>
</table>

The other branches are considered to have the phases almost balanced, with a distribution of 34%-33%-33%.

### III. Microgeneration with Energy Storage System

A Microgeneration system with the possibility of energy storage in parallel was simulated. The Microgeneration system considered in this work is a photovoltaic panel, while the energy storage system is formed by a battery bank.

#### TABLE IV

<table>
<thead>
<tr>
<th>Branch</th>
<th>Transmitted power [kVA]</th>
<th>Maximum current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – R1</td>
<td>142,623</td>
<td>205,86</td>
</tr>
<tr>
<td>2 – RR1</td>
<td>145</td>
<td>209,23</td>
</tr>
<tr>
<td>3 – RR2</td>
<td>75</td>
<td>205,86</td>
</tr>
<tr>
<td>4 – RL</td>
<td>75</td>
<td>205,86</td>
</tr>
</tbody>
</table>

The connection of the system to the grid is made by an inverter, converting DC waveforms into AC ones. However the system must also be able to capture energy from the grid. The converter that makes the connection to the grid can also work as a rectifier, depending on the required power flow. A reversible DC/DC converter is also connected to the battery bank, enabling bidirectional power flow.

To represent the system in the software Matlab/Simulink, the models of all components were developed. Considering a macro model, where the main focus is the balance of power, all constituents of the system were modeled by mathematical equations, simplifying the system. This way, the following conditions are assumed for the utilization of the model:

- Microgeneration system working in maximum power point (MPP)
- Sinusoidal waveforms established in the output

The equation that describes the dynamic of the current in the capacitor, according to Kirchhoff Laws:

$$ C \frac{dv_c}{dt} = i_{microG} + i_B - i_{in} \quad (2) $$

The voltage in the capacitor is represented by $v_c$, the current from MG by $i_{microG}$, while $i_B$ represents the current at the output of the boost converter (when working that way) and finally $i_{in}$ is the current entering the inverter. The panel, the battery bank (interconnected with a reversible DC/DC converter) and the inverter will be represented by current sources in the Simulink software.

#### A. Description of all components of the system

1) Photovoltaic Panel (PV)

The photovoltaic panel (PV) is considered to be in its MPP, supplying a power ($P_{PV}$) of 3450W. Bearing in mind the power balance equation of the PV and taking into account a delay ($T_d$) in the current $i_{microG}$, the following differential equation is obtained:

$$ i_{microG} = \frac{P_{PV}}{v_c} \frac{1}{1 + sT_d} \implies i_{microG} = \int d\frac{d i_{microG}}{dt} dt + i_{microG}(0) \quad (3) $$

Consequently the model of this component in Simulink can be seen in Fig.7:
2) Inverter
An inverter connects the system to the grid. It is assumed that its command is a three level pulse width modulation (PWM). This type of modulation eliminates most of the harmonic components. Thus, for the first harmonic the RMS value of the voltage is:

\[ V_{P1\text{RMS}} \approx \frac{V}{u_{c_{\text{max}}} \sqrt{2}} \]  \hspace{1cm} (4)

a) Capacitor at the entrance of the converter:
In order to have in the output a voltage (\( V_{AC} \)) with RMS of \( \sqrt{2}V_c \), the voltage in the capacitor must be higher than this value.

\[ V_c > \sqrt{2}V_{AC} \]  \hspace{1cm} (5)

Since the modulation index is approximately 0.78, a voltage of 500V was chosen for the capacitor. The sizing of the capacitor is made for the case of the converter being used as a rectifier. That means, as for the output filter of a rectifier, the sizing of \( C \) is calculated through \([12]\):

\[ C = \frac{P_{PV}}{\omega \Delta V_0} \]  \hspace{1cm} (6)

Assuming \( P_{PV} = 3450W \), \( V_c=500V \), \( \omega=2\pi f=2\pi 50 \) and \( V_0=V_c=500V \), the capacity is 4.4\( \cdot \)10\(^{-3}\)F.

b) Model of the inverter:
As observed above for the modelling of the PV, the mathematical equation of the power balance in the inverter is used to obtain the RMS value of the current injected into the grid (\( I_{AC} \)) and the one that enters the inverter (\( I_{\text{in}} \)):

\[ I_{AC} = \frac{\eta I_{\text{in}} V_{AC} \cos \phi}{V_{AC}} \]  \hspace{1cm} (7)

\[ I_{\text{in}} = \frac{V_{AC} I_{AC} \cos \phi}{\eta V_c} \]  \hspace{1cm} (8)

In order to synchronize the alternated current that is injected by the system with the voltage waveform of the grid, the system measures the voltage in the point of connection to the grid. By dividing it by the RMS value of that voltage, the sinusoidal form is obtained. Through the multiplication of this result and the RMS value of the current supposed to be injected, the waveform \( I_{AC}(t) \) is obtained.

3) Reversible DC/DC converter
For this converter (and considering the same method as in the other components), the RMS value of the current entering the converter and at its output is:

\[ \eta_{\text{B}} V_{\text{BAT}} I_{\text{BAT}} = \begin{cases} V_{\text{B}} I_{\text{B}} \\ \eta_{\text{B}} V_{\text{BAT}} I_{\text{B}} \end{cases} \]  \hspace{1cm} \eta_{\text{B}} = \frac{V_{\text{B}} I_{\text{B}}}{V_{\text{BAT}} I_{\text{BAT}}} \]  \hspace{1cm} (9)

B. Sizing of the Energy Storage System
The system chosen to be implemented in parallel with the photovoltaic panel was a battery bank. This energy storage technology was selected considering namely its fast response and long life cycle \([9,10]\). Between all types of batteries, the lithium battery was selected, specifically LiFePO\(_4\) battery, because of its high energy and power density, as well as efficiency \([9]\). This type of battery supports better consecutive charge/discharge cycles, typical for a system like the one developed in this paper.

<table>
<thead>
<tr>
<th>TABLE V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated Battery Characteristics [11]</strong></td>
</tr>
<tr>
<td><strong>Rated Voltage</strong></td>
</tr>
<tr>
<td><strong>Max. Charge Voltage</strong></td>
</tr>
<tr>
<td><strong>Cut-off Voltage</strong></td>
</tr>
<tr>
<td><strong>Rated Capacity</strong></td>
</tr>
<tr>
<td><strong>Service Time</strong></td>
</tr>
<tr>
<td><strong>Operate temperature</strong></td>
</tr>
</tbody>
</table>

The ESS was developed considering the connection of two batteries of the ones described in Table V in series. The value obtained in the output is 96V. In the software, considering the simplicity demanded for the computational calculation, both batteries are represented by a capacitor, which stores a certain amount of energy. It is known that the battery rated capacity is 100ah and it is assumed it will charge in 4h at 25Ah/h. Maximum charging current is therefore 25A. The value of the capacitor represented in Matlab/Simulink is obtained by:

\[ C = \frac{\Delta Q}{\Delta V} \]  \hspace{1cm} (10)

Considering the accumulated charge for 4h as 100ah and \( \Delta V \) as the difference between cut-off and maximum voltage in each battery, the representation of the batteries in Simulink is elaborated by a capacitor with 12162F.

C. Control of capacitor’s voltage (\( V_c \))
The control of this voltage can be achieved in two different ways, depending on the desired function for the system. In case it is not pretended to use the energy from the batteries, or they are discharged, a linear control through the injected current is applied. Otherwise, and using the energy stored in the batteries, the voltage is controlled using the converter connected to the energy storage system.
1) **Voltage control using the energy from the battery**
   The output current of the boost converter might be controlled so that:
   - $v_C = v_{C\text{ref}}$; or
   - Supplying or retrieving energy from the grid, according to the necessities of the system, maintaining the batteries voltage between $V_{\text{BATmax}}$ and $V_{\text{BATmin}}$.

   The controller is established considering the error in relation to the reference value: $e_{vC} = v_{C\text{ref}} - v_C$. With the help of Lyapunov theory, the function established has to be greater than zero:
   \[
   e_{vC}^2 > 0
   \]  
   (11)

   According to Lyapunov’s stability:
   \[
   e_{vC} \frac{de_{vC}}{dt} < 0 \iff \frac{de_{vC}}{dt} = -ke_{vC} \forall k > 0
   \]  
   (12)

   This way, and using equation (2) the output current of the is given by:
   \[
   i_B = kCe_{vC} - i_{\text{microG}} + i_{in}
   \]  
   (13)

   A simulation of the controller was tested, with the initial voltage of 450V.

   ![Fig. 4. Control of $v_C$ using energy from the battery](image)

2) **Linear control of capacitor’s voltage ($V_C$)**

   A linear control system might also be used to control the voltage $V_C$. This way the current injected to the grid should be regulated. A PI controller is implemented considering a delay of 20ms in the modulator of the inverter. That means the RMS value can’t be changed in a period or half a period, in order to not disturb the sinusoidal current injected into the grid. The following control system block diagram is considered:

   ![Fig. 8. Control system block diagram for the linear control of $V_C$](image)

   Using $b_k^2 = ab_k - b_{k+1}$ criterion, as in [12], and considering $a=2.7$, $T_c=50\text{ms}$ and $\alpha_r=0.1$ the compensator parameters are:

\[
\begin{align*}
T_z &= 0.146 \\
T_P &= -0.179
\end{align*}
\]  
(14)

2) **Battery charge and discharge control system**

   The battery can be charged either with energy coming from the grid or from the MG.

1) **Battery charging through energy coming from MG**

   Using equation (9) and considering as before a Lyapunov function based on the error of control $e_{VBAT} = v_{\text{BATref}} - v_{\text{BAT}}$, the battery current is considered to be in this case:

   \[
   I_{BAT} = -ck(v_{\text{BATref}} - v_{\text{BAT}})
   \]  
   (15)

   The state of charge (SOC) of the batteries considered in this paper is intimately related with the batteries voltage. Thus, it is assumed that the batteries are fully charged for a voltage value of 109.6V. In the following figure it is shown that the batteries charging process lasts approximately 4h as desired:

   ![Fig. 6. Battery charging process with energy produced by MG](image)

2) **Battery charging with energy from the grid**

   In this case it is expected that no current is generated from the MG device. The amount of power required by the batteries in every moment is calculated by:

   \[
   P_{\text{BAT}} = V_{\text{BAT}}I_{\text{BAT}}
   \]  
   (16)

   According to the directions of the electrical quantities defined in Fig.6, the power is assumed to be negative if the batteries are being charged. This way the injected current is given by:

   \[
   I_{AC} = \frac{P_{\text{BAT}}}{V_{AC}}
   \]  
   (17)

   Therefore the control scheme for the process of charging (and discharging) the battery from (into) the grid is the following:
The gain $K_{CB}$ is calculated in order to make the charge at constant current ($I_{BAT}=\text{constant}=25\text{A}$) until a SOC of 80%:

$$K_{CB} = \frac{I_{BAT}}{(V_{BAT\text{max}} - V_{BAT}(80\%))}$$  \hspace{1cm} (18)

Knowing that the charging current is 25A, $K_{CB}$ is 4,223.

IV. VOLTAGE-FREQUENCY REGULATION AND SYSTEM SUPERVISION

A. Voltage regulation

In order to regulate the voltage, the system may act on the reactive power and/or on the active power injected using for that the ESS capacity to inject or receive energy. Reactive power regulation is obtained through the phase shift of the injected current. If the system is not capable to regulate the voltage using the abovementioned methods, the active power of the microgenerator is reduced, positioning the device below the MPP.

1) Voltage closed loop regulation through the phase shift of the injected current by the system

Usually microgenerators inject a current in phase with the voltage waveform of the grid. However, by phase shifting the current, its waveform will be given by:

$$i_{MG|AE}(t) = \sqrt{2}I_{MG|AE}\!\!_{ef}\!\!\sin(\omega t + \phi_{MG|AE})$$  \hspace{1cm} (19)

Using trigonometric relations, equation (19), might be written as [13]:

$$\sin(\omega t + \phi_{MG|AE}) = \sin(\omega t)\cos(\phi_{MG|AE}) + \sin(\phi_{MG|AE})\cos(\omega t)$$  \hspace{1cm} (20)

Via devices implemented in the system, the RMS value, the amplitude or frequency of the phase voltage can be read. Hence, measuring the frequency of that voltage, a sinusoidal waveform with the same frequency might be produced as in equation (20). Afterwards, in accordance with [13], after the execution of some operations, the waveform $\sin(\omega t + \phi)$ is achieved. The RMS value of the output current, when the energy storage system does not influence the dynamic of the system is given by:

$$I_{MG|AE_{ef}} = \frac{P}{V_{MG|AE_{ef}}\cos(\phi)}$$  \hspace{1cm} (21)

According to Thévenin theorem the voltage variation in a variable reactive load might be expressed by [15]:

$$V = V^0 - jX_T I_S$$  \hspace{1cm} (22)

This way, for the voltage drop in a line composed by an equivalent resistive and inductive component:

$$|\Delta V| = \frac{V}{2} + \sqrt{\frac{V^2}{4} + P(R_{eq} - X_{eq}\tan(\phi_{MG|AE}))}$$  \hspace{1cm} (23)

In order to control the phase difference of the injected current, a closed loop regulation is applied, using a PI controller.

As explained in [13], $K_G \approx \frac{dV_{MG|AE}}{d\phi_{MG|AE}}$. Therefore the values for the integral and proportional terms, respectively $K_i$ and $K_G$ are given by:

$$K_G = \frac{1}{\frac{P}{\cos(\phi_{MG|AE})}}$$  \hspace{1cm} (24)

$$K_i = \frac{1}{4\omega^2 K_G T_d}$$  \hspace{1cm} (25)

Analyzing the variation of $K_G$ in relation to the phase angle and admitting $P=3450W$, $R_{eq}=0.64\Omega$ and $X_{eq}=10^{-1}\Omega$, the coefficient for the proportional term ($K_G$) is equal to -5. This value is close to the maximum gain, which in a closed loop system means instability. In accordance with equation (24) for the integral term is obtained: $K_i = -1$.

B. Frequency regulation

The frequency in the electrical grid should be maintained close to the nominal value of 50Hz (in Europe). Deviations in relation to the nominal value are intimately related with active power flow in the grid.

Supposing an isolated grid modeled by an equivalent generator the power balance is given by [15]:

$$P_M - P_e = \frac{dW_{\text{in}}}{dt}$$  \hspace{1cm} (25)

There are constant variations both in power supply and consumption. Because of the inertia of synchronous generators, frequency deviations do not assume greater proportions. However, there has been an increasing introduction of distributed generation mainly using RES. These, do not contribute in general to frequency control and most of them do not have inertia [14]. Consequently, and because of the intermittent character of RES the frequency deviations in those cases might be more frequent and problematic, primarily in isolated and weak electric grids.

1) Generator model

In pursuance of regulating the frequency through the action of MG with ES systems, a model of a three-phase synchronous generator was created. The mechanical equation of the system is vital for the modulation:
\[
\int \frac{d\omega}{dt} = T_m - T_e \tag{26}
\]

Multiplying equation (26) on both sides by \( \omega \) and obtaining that way a power equation, the value of the frequency might be calculated using:

\[
\omega = \int \frac{2(P_m - P_e)}{J} + c^2 t \tag{27}
\]

The model of the generator in the Simulink software is:

Fig. 9. Model of the generator in Matlab/Simulink

2) Control Scheme for the Frequency regulation

The primary frequency control does not keep the frequency in its nominal value. In order to reestablish the nominal value of the frequency, the secondary frequency control is used. It is proposed in this paper through the decentralized action of the MG and ES systems to help in the secondary frequency control, distributing the adjustment needed by every system implemented in the grid.

In order to do that, a model for the regulation of the frequency in an isolated grid was developed as in [15]. Every generation group is assumed to have an identical behavior and therefore in the Matlab/Simulink software they are all going to be represented as an equivalent generator [15]. To obtain the mathematical model of the grid, the relationship between the difference of the power balance and the resulting frequency deviation might be described as (using Laplace transformation) [15]:

\[
\Delta f(s) = \frac{K_r}{1 + sT_r} \left[ \Delta P_m(s) - \Delta P_C(s) \right] \tag{28}
\]

The factor \( K_r \) and the time constant \( T_r \), essential to obtain the mathematical model of the grid, can be calculated by [15]:

\[
K_r = \frac{1}{\varepsilon_f} \frac{P_{gir}}{P_C^0}, \quad T_r = 2H \frac{P_{gir}}{\varepsilon_f} \tag{29}
\]

Modeling the MG and ES system with the typical model for a converter \( \frac{1}{1 + sT_d} \), a system based on integral control is used to try to adjust the frequency to its nominal value. The reference value for the system is proportional to the integral of the frequency deviation:

\[
\begin{align*}
\text{Fig. 10. Control system block diagram of the frequency regulation}
\end{align*}
\]

As described in [15], the non-periodical regime is obtained when:

\[
K_i = \frac{T_r}{K_r} \frac{K_r E_r^2}{2T_r} \tag{30}
\]

\( E_r \) is considered to be the regulatory energy of the grid and can be obtained by:

\[
E_r = \frac{1 + \frac{K_r}{R}}{K_r} \tag{31}
\]

All values needed for the calculation of the generation group were based on the following characteristics assumed for the generator:

<table>
<thead>
<tr>
<th>Apparent Power</th>
<th>4MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Power</td>
<td>3.3MW</td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1500 RPM</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>150 kg m²</td>
</tr>
</tbody>
</table>

All values needed for the calculation of the generation group were based on the following characteristics assumed for the generator:

<table>
<thead>
<tr>
<th>TABLE VI EQUIVALENT GENERATION GROUP CHARACTERISTICS [16]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Power</td>
</tr>
<tr>
<td>Active Power</td>
</tr>
<tr>
<td>Rotational Speed</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Moment of inertia</td>
</tr>
</tbody>
</table>

The results for the simulation of the system in an isolated grid were obtained by connecting a system to each phase of the equivalent grid:

\[
\text{Fig. 11. Control scheme for frequency regulation in Simulink}
\]

The results for the simulation of the system in an isolated grid were obtained by connecting a system to each phase of the equivalent grid:

\[
\text{Fig. 12. Frequency Regulation of the modeled isolated grid}
\]

1 \( \varepsilon_f \) represents the elasticity of the loads.
2 \( R \) is the value defined for the droop characteristic of the system.
C. Supervision of the system

In order for all MG with ES systems to act in the same way and know how to respond to the conditions of the grid, as well as to simultaneously verify the conditions of the system itself, a supervisor was developed. This supervisor analyses some inputs, and chooses which controller should function so that the system behaves in the desired way.

The system functionality might be divided in two big components:

- Frequency or voltage regulation – If the hybrid system composed by MG and ES verifies that the RMS value of the voltage or frequency is out of the limits defined by the electric power quality parameters, it will react in order to regulate such values.

- Regular mode and maximization of the energy storage system possibilities – if there is no urgent need for voltage or frequency regulation the supervisor will try to maximize the potential of the energy storage system.

The SOC of the battery bank plays a very important role in the system and on how it may respond to the grid variables. It can vary from 100% (fully charged) to 0% (totally discharged). When the system is not regulating the voltage or frequency, the SOC is always between 20% or 80%. This means, that there is always a 20% margin to fully discharge or charge. This way, and in case there is an urgent need to regulate voltage or frequency, there is always a margin that can be used.

V. Simulation and results

The hybrid system previously developed was implemented in the grid described in section II. As explained before, various MG systems with ES were grouped together in equivalent systems, having an output power equal to the sum of all single systems that constitute the equivalent one. In the following table all groups of MG with ES are described. These can be constituted by one or more systems per phase:

<table>
<thead>
<tr>
<th>MG with ES group</th>
<th>Number of systems per phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-1-1</td>
</tr>
<tr>
<td>2</td>
<td>3-3-3</td>
</tr>
<tr>
<td>3</td>
<td>0-1-1</td>
</tr>
<tr>
<td>4</td>
<td>1-0-1</td>
</tr>
<tr>
<td>5</td>
<td>1-1-1</td>
</tr>
<tr>
<td>6</td>
<td>0-0-1</td>
</tr>
</tbody>
</table>

Three big scenarios were analyzed, namely a situation of high load (70% of nominal power), a scenario of almost no load (2% of nominal power) and a voltage dip in the MV. The first branch is the object of study in this paper, therefore it will be analyzed with more detail.

A. High load scenario

In this first scenario the grid was firstly analyzed without any MG or ES system. Due to the high transited power, there is a huge voltage drop along the first branch. The voltage profile in the first branch is shown:

![Fig. 14. Voltage Profile in the first branch for the case of a high load scenario without MG or energy storage.](image)

In this scenario of high load, it is expected the price of electricity to be high. Therefore it is advantageous for consumers to sell energy to the grid. In this case, it is simulated a scenario where all ESS inject power into the grid. However every system starts with a different initial SOC. The following initial SOC will be considered:

<table>
<thead>
<tr>
<th>MG with ES group</th>
<th>Initial SOC of the ESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>70%</td>
</tr>
<tr>
<td>4</td>
<td>40%</td>
</tr>
<tr>
<td>5</td>
<td>30%</td>
</tr>
<tr>
<td>6</td>
<td>50%</td>
</tr>
</tbody>
</table>

![Fig. 15. Voltage Profile in the first branch for the case of a high load scenario with the injection of power from every ESS.](image)
B. Low load scenario

In this scenario the power consumed is about 2% of the nominal power. This is a typical situation of a summer afternoon where everybody leaves home for a walk or to go to the beach. Since the load factor is very low, a minimal voltage drop along the first branch is expected.

Fig. 16. Voltage Profile along the first branch for the low load scenario without any MG or ESS

However, it can be seen that when all MG systems of the first branch are working and injecting a current into the grid, there is a reversal of the power flow. This turns out to produce an overvoltage mainly in the MG systems that are far away from the substation (Fig. 20.).

Fig. 17. Voltage Profile along the first branch for the low load scenario with MG systems injecting power

1) Implementation of supervision in all MG with ES systems

The overvoltage that occurred in the low load scenario was mitigated through different methods. The SOC of every ESS was the one defined in table VI, if nothing in contrary is said.

a) Supervision implemented in the last MG with ES system:

Fig. 18. Voltage profile along the first branch for the case of supervision implemented in the last MG with ES system (group 6)

b) Supervision implemented in the last MG with ES system, with ESS fully charged (SOC = 100%)

Fig. 19. Voltage profile along the first branch for the case of supervision implemented in the last MG with ES system (group 6), but with SOC=100%.

In this case the regulation was made only through the reactive power method. In the following figure it can be observed the RMS value of the voltage in the point of connection of the system to the grid considering the phase angle:

Fig. 20. RMS value of the voltage in the point of connection of the system to the grid considering the phase angle

Supervision in all systems of the first branch, considering the MG and ES systems close to the substation (Groups 1, 2, 3 and 4) with initial SOC=20% and the ones far away (5 and 6) with SOC=100%.

Fig. 21. Voltage profile along the first branch for the case of supervision implemented in every MG with ES system.

Due to the action of the MG and ES systems that are close to the substation, the overvoltage is mitigated. Considering the supervision system developed, the systems in reaction to the conditions of the grid and the SOC of the ES, do not inject as much active power as before using part of the energy generated by the MG to charge the energy storage system.

Fig. 22. Voltage profile along the first branch with supervision installed in every systems implemented on the first branch

C. Voltage dip

A scenario of a voltage dip was created. This situation lasts for 5 periods of the grid. During that time the RMS value of the voltage in the MV decreases to 90% of its nominal value. The
voltage profile along the first branch (R1) during the voltage dip is the following (without any ESS working)³:

![Voltage profile along the first branch during a voltage dip of 90% in the MV](image)

**Fig. 23. Voltage profile along the first branch during a voltage dip of 90% in the MV**

With the systems of MG and ES implemented it is expected that the ESS all together inject power into the grid in order to mitigate the voltage dip. Considering an SOC of 80% in all systems present in the first branch, and with a collective injection of power produced by all systems, the dip is mitigated in the phase T. Although the RMS value in the other phases rises, there is not enough current injected, mainly in the last buses, in order to mitigate the dip.

![Voltage Profile during the voltage dip with the injection of power by the batteries](image)

**Fig. 24. Voltage Profile during the voltage dip with the injection of power by the batteries**

VI. CONCLUSION

The focus of this paper is the development of a MG system with ES that, together with other similar systems, could impact on the electric power quality of a LV grid, especially in the case of an isolated grid.

After the model of a LV grid and one of the system were created in the software Matlab/Simulink (described in Section II and III), a supervisor was developed with the goal of controlling the power flow in each one of the systems. The supervisor should behave according to the conditions of the grid and the SOC of the ESS, and its function is essential on the development of a decentralized action of all devices.

In Fig. 17 (case of a low load scenario) when all microgenerators are injecting power into the grid, it can be seen the emergence of an overvoltage at the end of the first branch. This overvoltage was mitigated through several ways and all of them proved to work. Either by implementing a supervisor on the last MG with ES system (the one that reads the overvoltage on its terminals), or by applying the supervision system to all groups of devices installed in R1.

In the first case, the system proved to work, either using the capabilities of the system to inject the power generated by MG into the ESS (Fig. 18), or in the case of the ESS to be fully charged. In this last case, resorting on the reactive power method described in IV.A.1). These results can be analyzed in Fig. 19 and Fig. 20. Secondly, assuming all systems implemented in the first branch to have supervision, the voltage could also be regulated. In the case of having the ESS of the groups further away from the substation fully charged, the action of the ones closer to the substation was enough to mitigate the overvoltage (Fig. 21).

Also in the case of a voltage dip, the systems were capable to mitigate the dip in one of the phases. However not enough current was injected to mitigate the situation in every phase of the three phase system.

The impact of the decentralized action of the systems in the power quality was this way acknowledged. Either by avoiding over- and undervoltages or by regulating the frequency, according to the obtained results, such systems can have a positive impact, especially in the case of an isolated grid.

REFERENCES


