Development and design of a mobile power plant in the form of a standalone power supply

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Abstract. The work is devoted to increasing the energy efficiency of uninterruptible power supplies in enterprises with a continuous technological cycle. During the operation of continuous technological processes, a power failure even for a short period of time leads to significant economic damage. The most modern technical solution to this problem is the creation of guaranteed power supply systems using diesel power plants (DES) and uninterruptible power supplies (UPS), based on rechargeable batteries and supercapacitor modules. It is proposed to use supercapacitors in parallel with the battery in order to ensure the stable operation of the diesel generators under starting conditions, as well as during load transfer. In this case, when using supercapacitors, it becomes possible to reduce the power capacity of the generators and uninterruptible power supplies along with the size of their batteries. Therefore, the cost of the solution decreases and its energy efficiency increases. To test the efficiency of the system, a computer model was created using MATLAB. The system showed a successful operation in supplying the load from all the power sources as well as maintaining Unity Power Factor at the Mains/Generator side.

1. Introduction

The transmission of electricity from district substations and power plants of the main electric network to the consumers through power transmission lines is associated with short-term power outages at the consumer's level. These violations can take the form of voltage dips or a complete failure of power supply facilities. This failure can be caused by various factors, mainly short circuits or damage resulting from lightning strikes. A power outage for oil and gas companies, even for a short period of time, can lead to significant economic losses.

In the case of oil producers, oil production units are considered the most sensitive to interruptions in power supply. Even short-term power failures for such installations can lead to blackouts and, as a result, to a disruption of the process. The time needed to restore their normal operation, may vary from several tens of minutes to several hours. Consequently, this can lead to large losses in oil production. The electric centrifugal pumps (ECPs) are considered among these units. Their drives use induction motors (IM) having a power range from 12 to 500 kW.

Many investigations were made about the influence of the input voltage disturbances on the operation's stability of the IM of the electrical centrifugal pumps. These investigations showed that the decrease of the input voltage at the pumps' terminals to 60% of the nominal voltage ($V_N$), for a duration of 0.15 s, causes losses in the stability and subsequent stops [3]. In case of an emergency on one of the power lines, the duration of the intervention of the backup source lasts up to several
seconds. This is mainly due to the duration of the automatic transfer switch device (ATS). Therefore, a stand-alone and self-contained option of power supply of the field is certainly economically justified.

For the users considered under the 1st category, it is necessary to maintain a redundant power supply in a hot reserve. However, this solution is quite expensive because of the fuel consumption associated with the operating costs, and also because of the deterioration and exhaustion of the diesel engine. On the other hand, if the redundant power supply is kept in cold reserve, for any power outage or any decrease in the voltage level in the power supply system (PSS), the startup duration of the redundant units and their readiness to supply power, can last up to 30 s. [1-7]

Given the above reasons, it becomes necessary to find various technical means to maintain the required voltage level regardless of what type of failure can occur in the network. The main idea of the work begins with the introduction of a power storage module capable of supplying a load of 110 kW (including induction motors feeding submersible pumps) in rural areas for the electric plants with a continuous technological cycle of oil and gas production. For this purpose, the proposed solution consists in installing a secondary / backup diesel generator (in cold reserve) in parallel with the battery banks and supercapacitor modules. When a failure or instability occurs in the main power network, the batteries and supercapacitors’ system will interfere to solve the instability problem leading to a behavior similar to PFC. If the fault goes beyond interference of the stored energy, or if the condition of the batteries and supercapacitor is low, the generator takes over the load. In the event of a failure in the network, the accumulated energy in the battery and supercapacitor modules should be enough to power the load until the diesel generator starts and is ready to feed the load.

The concept of the solution is to combine the generator and the energy storage system together with the elements of the power electronics converters on one trailer truck, in a form of a mobile power station that can be used to power the required loads of mobile asynchronous motors or any other mobile load. Such mobile station can also be used as the main power source for exploration works, geodetic and geodesic works, in addition to other types of work, for example, vertical, inclined and horizontal drilling in order to search, detect and prepare mineral deposits. This operation requires an understanding of how to integrate all the elements into a single network that can monitor the status of the operation, make decisions and give orders to the proper equipment for taking action [8-10].

In this regard, a variety of schemes can be proposed, however, we suggest the following components:

- A generator supplying an IGBT based AC to DC rectifier with UPF capability, the rectifier supplies a DC bus;
- Energy Storage System (ESS) consisting of:
  - A set of batteries supplying a DC-DC SEPIC converter installed in parallel with the generator rectifier and connected to the DC link;
  - A supercapacitor module supplying another DC-DC SEPIC converter mounted in parallel to the battery module block to feed the DC link;
- A capacitor in the role of a DC link. The capacitor is installed at the input terminals of a converter, which feeds the load (the induction motor).

2. ESS, Converters and their Control

Controlling DC/DC converters can be implemented by various circuit topologies. Among these topologies basic and commonly used converters, like the buck converters, boost converters in addition to more complicated converters, for example Cuk, Zeta and SEPIC converters. The main feature of such converters is their ability to convert voltages in both modes, the step-up mode as well as the step-down mode. However, with SEPIC converter the polarity of the output voltage is conserved, which is an important advantage over its competitive converters. One more advantage of SEPIC is its capability to offer an input/output isolation. Therefore, selecting such converter for ESS applications is definitely advantageous [11-13].
Having decided on components of the solution, the parameters of the SEPIC converters are designed using small signal analysis, together with their controllers for optimal operation of the required application [14-15].

The SEPIC converters will be tested with the battery and supercapacitor modules.

![SEPIC Converter schematic.](image)

To evaluate the relationship between the various converter’s variables, three models of the converter will be obtained. We will start in getting the large signal model, which is the general model of the converter. Then we will split it into small signal and steady state models. This evaluation will give us a clear view how would be the control scheme. [16-17]

But first for the sake of simplicity let us consider the following conventions:

\[
\begin{align*}
\dot{v}_1 &= \frac{d v_{c1}}{d t}, \quad \dot{v}_2 = \frac{d v_{c2}}{d t}, \quad i_1 = \frac{d i_{L1}}{d t}, \quad i_2 = \frac{d i_{L2}}{d t} \\
v_2 &= v; \quad \text{Output voltage} \\
d &= D + \dot{d}; \quad \text{Duty cycle and } D = \frac{V_{ref}}{V_{ref} + V_g} \\
v_g &= V_g + \tilde{V}_g; \quad \text{Input voltage} \\
v_1 &= V_1 + \tilde{V}_1 \\
v_2 &= V_2 + \tilde{V}_2 \\
i_1 &= I_1 + \tilde{I}_1 \\
i_2 &= I_2 + \tilde{I}_2
\end{align*}
\]

Where \( \mathbf{m}, \mathbf{M} \) and \( \mathbf{\dot{m}} \) represent respectively the large, DC and the small parts of a signal. And \( \mathbf{\dot{m}} \) is the derivative with respect to time of \( \mathbf{m} \).

The three models of the converter:

- The averaged large signal model:

\[
\begin{bmatrix}
i_1 \\ i_2 \\ v_1 \\ v_2
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & -1(1-d) & -1(1-d) \\
1-d & -d & \frac{L_1}{1} & \frac{L_1}{1} \\
\frac{C_1}{1} & \frac{C_1}{1} & 0 & 0 \\
\frac{1-d}{1} & \frac{1-d}{1} & 0 & -1
\end{bmatrix}
\begin{bmatrix}
i_1 \\ i_2 \\ v_1 \\ v_2
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_1} \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
\frac{V_g}{u} \\
0 \\
0 \\
0
\end{bmatrix}
\]

(9)
\[
\frac{v}{Y} = \begin{bmatrix} 0 & 0 & 0 \\ \dot{i}_1 \\ \dot{v}_1 \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{v}_g \end{bmatrix}
\]

- Steady state model or the DC model:

\[
\frac{(V)}{Y} = - \begin{bmatrix} 0 & 0 & 0 \\ \dot{i}_1 \\ \dot{v}_1 \end{bmatrix}
\begin{bmatrix}
0 & 0 & -1(1-D) & -1(1-D) \\
0 & 0 & \frac{L_1}{D} & \frac{L_1}{D} \\
1-D & -D & \frac{L_2}{L_2} & -1(1-D) \\
\frac{C_1}{C_1} & \frac{C_1}{C_1} & 0 & 0 \\
1-D & 1-D & 0 & -1 \\
\frac{C_2}{C_2} & \frac{C_2}{C_2} & & \frac{1}{RC_2}
\end{bmatrix}
\begin{bmatrix}
1 \\
0 \\
0 \\
0 \\
0 \\
B
\end{bmatrix}
\]

- Small signal model:

\[
\frac{\ddot{i}_1}{\dot{v}_1} = \begin{bmatrix}
0 & 0 & -1(1-D) & -1(1-D) \\
0 & 0 & \frac{L_1}{D} & \frac{L_1}{D} \\
1-D & -D & \frac{L_2}{L_2} & 0 \\
\frac{C_1}{C_1} & \frac{C_1}{C_1} & 0 & -1 \\
1-D & 1-D & 0 & \frac{1}{RC_2} \\
\frac{C_2}{C_2} & \frac{C_2}{C_2} & & \frac{1}{RC_2}
\end{bmatrix}
\begin{bmatrix}
\ddot{i}_1 \\
\ddot{v}_1 \\
\ddot{v}_2 \\
\dot{x}
\end{bmatrix}
+ \begin{bmatrix}
V_1 + V_2 \\
\frac{V_1 + V_2}{L_1} \\
\frac{L_2}{C_1} \\
\frac{-l_1 - l_2}{C_2} \\
\frac{-l_1 - l_2}{C_2} \\
0
\end{bmatrix}
\frac{\ddot{v}_g}{\dot{u}_{dc}}
\]

\[
\frac{\ddot{v}}{Y} = \begin{bmatrix} 0 & 0 & 0 \\ \dot{i}_1 \\ \dot{v}_1 \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{v}_g \end{bmatrix}
\]

This analysis will help to get the transfer function of the converter’s open loop in order to study its behavior, and to perform the assessment of the system’s reaction.

Deriving the state space equation of the small signal model, we can now study the behavior of the system at the transient time:

\[
\dot{x} = Ax + Bu
\]
\[
y = Cx + Du
\]

Converting the above system into Laplace form:

\[
\{pX(p) = A.X(p) + B.U(p)
\]
\[
Y(p) = CX(p) + DU(p)
\]

\[
\begin{cases}
X(p) = [pl - A]^{-1}BU(p) \\
Y(p) = C[pl - A]^{-1}BU(p) + DU(p)
\end{cases}
\]
Having set our relationships, we can now derive the open loop transfer function of the output voltage $\hat{v}$ of the converter with respect to the duty cycle $\hat{d}$:

$$\frac{\hat{v}}{\hat{d}} = C[pI - A]^{-1} B_d$$

(17)

Where,

$$B_d = \begin{bmatrix} V_1 + V_2 \\ \frac{L_1}{V_1 + V_2} \\ \frac{L_2}{-I_1 - I_2} \\ \frac{C_1}{-I_1 - I_2} \\ \frac{C_2}{-I_1 - I_2} \end{bmatrix}$$

(18)

This system is mainly powered by a set of batteries and/or supercapacitors, where each set will provide a DC voltage of around 500 V. As the batteries or supercapacitor modules provide power to the load, their output voltage begins to change and decrease. Thus, the role of the SEPIC converter is to increase the supplied voltage to 800 volts and maintain a constant output voltage on the DC-Link bus supplying a load (an induction motor with a power) of 110 kW.

And so, the design assumptions for the converter took into account these factors and using the concept of small ripple analysis, the following design basis parameters were calculated.

| Design Parameters            | Value                                      |
|------------------------------|--------------------------------------------|
| Switching Frequency          | 20 KHz                                     |
| Input Voltage                | 500 V                                      |
| Output Voltage               | 800 V                                      |
| Resistance Load             | 5.333Ω (representing a maximum load of 120 KW) |
| Steady-State duty cycle $D$  | 0.6154 (calculated from (2.22))            |
| $\Delta I_{L1}$              | 15% of $I_{L1}$                            |
| $\Delta I_{L2}$              | 15% of $I_{L2}$                            |
| $L_1$                        | 0.2136 mH                                  |
| $L_2$                        | 0.3418 mH                                  |
| $\Delta V_{C1}$              | 1% of $V_{C1}$                             |
| $\Delta V_{C2}$              | 1% of $V_{C2}$                             |
| $C_1$                        | 0.4615 mF                                  |
| $C_2$                        | 0.2884 mF                                  |

These assumptions are taken into account during the design of the converter, and using computer simulation, the values of the converter’s parameters are used to obtain the transfer function of the open circuit of the small signal output voltage of the converter "$\hat{v}$" with respect to the small signal duty cycle "$\hat{d}$":

$$\frac{\hat{v}}{\hat{d}}(p) = \frac{-1.352 \times 10^6 p^3 + 1.318 \times 10^{10} p^2 - 5.273 \times 10^{12} p + 5.141 \times 10^{16}}{p^4 + 650 p^3 + 7.8 \times 10^6 p^2 + 2.535 \times 10^9 p + 1.521 \times 10^{13}}$$

(19)
Since the derived transfer function is of the 4th order type, this function is difficult to control, therefore, using the Padé approximation methods, it is reduced to the 2nd order and the control concept will be based on this resulting transfer functions:

\[
\frac{\dot{d}}{d}(p) = \frac{-1.352 \times 10^6 p + 1.318 \times 10^{10}}{p^2 + 650 p + 3.9 \times 10^6}
\]  
(20)

Since the main transfer function is derived using the small signal analysis, the output of the PI controller is the small signal duty cycle \(\hat{d}\), therefore if we feed the PWM with the large signal “\(d\)” in equation (3), we will expect a faster response. For this purpose, we will add the steady state part of the duty cycle “\(D\)” to the input signal of the PWM as shown in the figure 2. The output response of the improved controller is shown to be far better than the previous methods providing a rising time around 0.558 ms (figure 3). [16-19]

\[
d = \hat{d} + \frac{V_{ref}}{V_{ref} + V_g}
\]  
(21)

| Table 2. Converter Rise Time for PI Controllers. |
|------------------------------------------------|
|                                      | \(t_{10}\%\) (ms) | \(t_{90}\%\) (ms) | Rise Time (ms) |
|------------------------------------------|----------------|----------------|---------------|
| PI Controller                            | 0.36           | 28             | 27.64         |
| Upgraded IMC based PI Controller         | 0.24           | 0.798          | 0.558         |

Figure 2. SEPIC Converter schematic with upgraded PI controller.
Figure 3. Converter output in response to PI and PI\textsuperscript{Upgraded} controllers.

The converter and its controller will be tested by applying non-ideal DC sources to its input, and their response will be shown in the figures.

The battery model used from Matlab/Simulink, imitates the behavior of a Li-Ion Battery. For this matter, the following data of the battery has been considered.

Table 3. Battery Parameters.

| Battery Parameters           | Value |
|------------------------------|-------|
| Nominal Voltage (V)         | 3.3   |
| Rated Capacity (Ah)         | 2.05  |
| Initial State of Charge SOC (%) | 100   |
| Battery Response Time (s)   | 0.1   |
| Number of Batteries in Series | 152   |
| Number of Batteries in Parallel | 300   |

The response of the converter due to the input of a battery as a non-ideal DC-source showed very minor oscillations at the transient time, however the ripple in the output voltage, (see figure 4), was conserved (up to 1% of output voltage), which proves the right design of the converter. On the other hand, the rise time of the voltage is calculated to be 0.538 ms as reflected in ‘figure 5’.
Figure 4. Converter output in response to battery input.

Figure 5. Converter output Rise Time in response to battery input.
On the other hand, the supercapacitor used in the simulation imitates the Stern model behavior. The parameters used for the supercapacitor are presented in table 4.

| Supercapacitor Parameters | Value  |
|----------------------------|--------|
| Nominal Voltage (V)        | 2.7    |
| Rated Capacitance (F)      | 3500   |
| Equivalent Series Resistance (mOhms) | 8.9 |
| Initial Voltage (V)        | 585.9  |
| Number of Supercapacitors in Series | 185 |
| Number of Supercapacitors in Parallel | 300 |
| SOC (%)                    | 100    |
| Operating Temperature (°C) | 25     |

The response of the supercapacitor showed similar results to the battery with a rise time of 0.6 ms (see figures 6 and 7).

![Converter Output in Response to Supercapacitor Input](image)

**Figure 6.** Converter output in response to supercapacitor input.
Figure 7. Converter output Rise Time in response to supercapacitor input.

A combined plot for 2 converter outputs, one powered by a battery set, the other by a supercapacitor set, is shown in ‘figure 8’.

It is worth to note that the simulation results showed that the higher the initial voltage (i.e. the state of charge SOC) of the battery or the supercapacitor and the bigger the number of parallel modules installed (i.e. the capacitance of the batteries or the supercapacitor’s set), the faster their response will be. This justifies how the battery reacts faster than the supercapacitor. Another observation shows that the supercapacitor’s converted voltage settles up to steady state faster than that of the batteries as shown in ‘figure 8’.

Each of the battery source, and the supercapacitor power source are constructed from a set of battery and supercapacitors cells respectively, connected in parallel and in series. Due to imperfection in manufacturing, there will be a variation in the internal resistances in each cell, and the real capacity of each unit will not be uniform, this will cause a leakage current to flow between the cell either in the battery block, or the super capacitor block. To solve or attenuate this problem, equalization or cell balancing has to be used. Many methods for cell balancing are proposed, they can vary in cost and speed. One of the very effective balancing technique is using transistors in parallel to the supercapacitor, to render their voltages equivalent to an intermediate level. Another method that is effective to a certain range, but has a slow balancing rate, is to use resistors instead of the transistors. This method consumes some of the energy stored in the blocks but is cheaper and easily implemented [21].
3. Universal Bridge Rectifier and UPF

The second part of the solution will focus on the development of an AC-DC rectifier system supplying an 800 V DC link and its corresponding controller.

The rectifier is mainly fed from 2 sources: a centralized power source and a standby generator operating in the cold reserve mode. By the time the generator starts, the energy storage module will power the 110-kW load.

In order to successfully complete this scenario, the rectifier must be able to provide a unity power factor (UPF) operation and compensate for all interference introduced into the main network or to the generator side. Therefore, the amount of consumed power will decrease and the system component sizes will be reduced, further the network harmonic distortions will be eliminated providing a “clean” network voltage and a higher equipment life. In addition to reducing false alarms and triggering of control and protection devices [10]. In this regard, the rectifier will operate in bidirectional power transmission and unity power factor mode using a vector control strategy, in particular, a voltage-oriented control (VOC) method. To achieve this task, a universal bridge topology (figure 9) will be used, where “v_L” is the line voltage, and “v_C” is the bridge converter voltage that will be controlled from the DC side and “V_DC” is the DC-Link voltage. “R” and “L” represent respectively the line resistance and inductance [22].

![Universal Bridge Inverter Schematic](image)

**Figure 8.** Converter output in response to battery and supercapacitor inputs.

**Figure 9.** Universal Bridge Inverter Schematic.
The control method uses the internal model control concept (IMC) and a cascade control scheme. The main idea relates to controlling the DC link voltage through an external circuit, and the currents \(i_d\) and \(i_q\) through an internal circuit having a reference phase angle between the line current and the converter input voltage. To achieve UPF, the “q” component reference of the current is assumed to be zero which leads to controlling the angle “\(\delta\)” in ‘figure 10’ [22- 27].

\[\text{Figure 10. Phasor Diagrams: Typical - Rectification at UPF - Regeneration at UPF.}\]

The mathematical model is the bases of the rectifier design, it is implemented by analyzing the 3-phase power system, reflecting them in the proper reference frame and deriving the rectifier governing dynamics.

The three-phase line voltage and current are described as follows:

\[
\begin{bmatrix}
  v_a \\
  v_b \\
  v_c 
\end{bmatrix} = E_m \begin{bmatrix}
  \cos(\omega t) \\
  \cos(\omega t - \frac{2\pi}{3}) \\
  \cos(\omega t - \frac{4\pi}{3}) 
\end{bmatrix} 
\]

\[
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c 
\end{bmatrix} = I_m \begin{bmatrix}
  \cos(\omega t + \varphi - \frac{2\pi}{3}) \\
  \cos(\omega t + \varphi - \frac{4\pi}{3}) 
\end{bmatrix} 
\]

where “\(E_m\)” and “\(I_m\)” and “\(\omega\)” are amplitudes of the phase voltage (current) and angular frequency, respectively, with the assumption of no neutral connection, therefore the sum of the currents will be null:

\[i_a + i_b + i_c = 0\] (24)

This representation can be reflected in the \(\alpha\-\beta\) reference frame using the Clarke transformation, to be represent as 2 quantities (real and imaginary) instead of 3 components. Hence the below space vector will be introduced:
Where K is the space-vector scaling constant and chosen to be equal to “1” representing the Peak-value scaling or Amplitude invariant scaling.

The following assumptions are set for consideration of Space Vector Pulse Width Modulation (SVPWM) in the rectifier model:

1- $f_s$ is the switching frequency and $T_s$ is the switching period of the PWM:

$$f_s = \frac{1}{T_s}$$  \hspace{1cm} (26)

2- $S_i$ is the switching function defined as:

$$S_i = \begin{cases} 
1, & \text{if upper switch is ON} \\
0, & \text{if lower switch is ON}\end{cases}, i = \text{phase a, b or c}$$  \hspace{1cm} (27)

3- $S_a = \frac{T_a}{T_s}$ where $T_a$ is the conduction time of $v_a$. Similarly the same assumption applies to $v_b$ and $v_c$.

4- Over one period $T_s$ the average output voltages $v_{aN}$, $v_{bN}$ and $v_{cN}$ with respect to the negative dc bus “N” are expressed as:

$$\begin{bmatrix}
v_{aN} \\
v_{bN} \\
v_{cN}
\end{bmatrix} = \frac{V_{DC}}{T_s} \begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix}$$  \hspace{1cm} (28)

5- On the other hand, and considering a balanced system, the average neutral point voltage can be obtained by:

$$v_{0N} = \frac{1}{3}(v_{aN} + v_{bN} + v_{cN}) = \frac{1}{3}V_{DC}(T_a + T_b + T_c) = \frac{1}{3}V_{DC}(S_a + S_b + S_c)$$  \hspace{1cm} (29)

Having set this, and during one switching period $T_s$ the following relationship between the conduction time of each phase and the voltages is obtained:

$$\begin{bmatrix} v_{a0} \\ v_{b0} \\ v_{c0} \end{bmatrix} = \begin{bmatrix} v_{aN} - v_{0N} \\ v_{bN} - v_{0N} \\ v_{cN} - v_{0N} \end{bmatrix} = \frac{1}{3}V_{DC} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix} = \frac{1}{3}V_{DC} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$  \hspace{1cm} (30)

And therefore:

$$\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \begin{bmatrix} v_{a0} - v_{b0} \\ v_{b0} - v_{c0} \\ v_{c0} - v_{a0} \end{bmatrix} = V_{DC} \begin{bmatrix} S_a - S_b \\ S_b - S_c \\ S_c - S_a \end{bmatrix}$$  \hspace{1cm} (31)

The matrix $S$ is defined to be the switching matrix. More about space vector pulse width modulation is shown in the references [28].

Having decided on the UPF, and referring to ‘figure 10’ pertaining the regeneration at UPF and ‘figure 9’, the voltage equations for a balanced three-phase system without a neutral connection can be written as:

$$v_L = Ri + L \frac{di}{dt} + v_c$$  \hspace{1cm} (32)

Elaborated in matrix form:
\[
\begin{bmatrix}
v_{La} \\
v_{Lb} \\
v_{Lc}
\end{bmatrix} = R \begin{bmatrix}
i_{a} \\
i_{b} \\
i_{c}
\end{bmatrix} + L \begin{bmatrix}
di_{a} \\
di_{b} \\
di_{c}
\end{bmatrix} + \begin{bmatrix}
v_{Ca} \\
v_{Cb} \\
v_{Cc}
\end{bmatrix}
\]

(33)

On the other hand, applying Kirchhoff current law at the DC-link node in ‘figure 8’ the following relationship is derived:

\[
i_C = C \frac{dV_{DC}}{dt} = i_{DC} - i_{Load} = (S_a i_a + S_b i_b + S_c i_c) - i_{Load}
\]

(34)

By applying Clarke and Park Transformations, the Converter’s Mathematical Model can be represented in \(\alpha-\beta\) reference and d-q reference frame as follows:

\[
v_{La\beta} = R i_{a\beta} + L \frac{di_{a\beta}}{dt} + v_{Ca\beta}
\]

(35)

\[
\begin{bmatrix}
v_{La} \\
v_{Lb}
\end{bmatrix} = R \begin{bmatrix}
i_{a} \\
i_{b}
\end{bmatrix} + L \frac{di_{a}}{dt} \begin{bmatrix}
i_{a} \\
i_{b}
\end{bmatrix} + \begin{bmatrix}
v_{Ca} \\
v_{Cb}
\end{bmatrix}
\]

(36)

\[
C \frac{dV_{DC}}{dt} = \frac{3}{2} K(S_a i_a + S_b i_b) - i_{Load}
\]

(37)

\[
v_{dq} = v_{a\beta} e^{-j\beta} = (v_a + jv_b) e^{-j\beta}
\]

(38)

\[
v_{Ldq} = R i_{dq} + L \frac{di_{dq}}{dt} + j\omega L i_{dq} + v_{Cdq}
\]

(39)

\[
\begin{cases}
v_{ld} = R i_d + L \frac{di_d}{dt} - \omega L i_q + v_{Cd} \\
v_{Lq} = R i_q + L \frac{di_q}{dt} + \omega L i_d + v_{Cq}
\end{cases}
\]

(40)

\[
C \frac{dV_{DC}}{dt} = \frac{3}{2} K(S_a i_d + S_q i_q) - i_{Load}
\]

(41)

It is useful to derive the instantaneous power relationships:

\[
S_{power} = v \times i^*; \quad i^* = Complex \ Conjugate \ of \ i
\]

(42)

\[
\begin{cases}
P = Re{v \times i^*} = Re{v_{a\beta} \times i_{a\beta}^*} = Re{v_{dq} \times i_{dq}^*} \\
Q = Im{v \times i^*} = Im{v_{a\beta} \times i_{a\beta}^*} = Im{v_{dq} \times i_{dq}^*}
\end{cases}
\]

Considering ideal positive sequence space vectors and the reference being the voltage:

\[
v_{a\beta} = KE_m e^{j\omega t}
\]

(44)

\[
i_{a\beta} = KL_m e^{j\omega t + \phi}
\]

(45)

Where \(\phi\) being the phase angle between the voltage and the current, \(E_m\) and \(I_m\) are the peak values or amplitudes and \(E\) and \(I\) are the RMS-values the power relationships will be as follows:

\[
\begin{cases}
P = \frac{3}{2} K E_m I_m \cos \phi = 3KEI \cos \phi \\
Q = \frac{3}{2} K E_m I_m \sin \phi = 3KEI \sin \phi
\end{cases}
\]

(46)
Assuming a UPF (46) becomes:
\[
P = \frac{3}{2} KE_m I_m = 3KEI
\]
\(Q = 0\)  
(47)

For the rectifier to properly function, a minimum DC-link voltage is needed to obtain undistorted current waveforms. To have a full control of the rectifier, its six diodes must be polarized negatively at all value of ac-voltage supply. To keep the diodes blocked, a dc-link voltage needs to kept higher than the peak dc-voltage generated by the diodes alone.

For the rectifier to properly function, a minimum voltage in the DC circuit is necessary to obtain undistorted current signals. In order to have a complete control over the rectifier, all its diodes must be negatively polarized at all AC voltages. To maintain the diodes in the blocked mode, the voltage at the DC-link must be higher than the peak DC voltage generated by the diodes alone.

In theory a diode rectifier produces a maximum dc output voltage equal to the peak value of line-to-line RMS voltage [22].

In addition, the DC link voltage \(V_{dc}\) must be higher than the minimum required DC-link voltage to allow current control and avoid overmodulation [29]. In case of SV PWM it can be determined as follows:
\[
V_{dc} > \sqrt{2} V_{LL(RMS)} = \sqrt{2} \sqrt{3} V_{LN(RMS)} = \sqrt{3} V_{LN(P(EAK)} = 565.7\ V
\]
(48)

Referring to (39) and neglecting the resistor for its low value, the relationship can be rewritten as:
\[
L \frac{dI_{dq}}{dt} = v_{Ldq} - j\omega L I_{dq} - v_{cdq}
\]
(49)

It defines the direction and rate of current vector movement leading to the following definition of \(V_{DCmin}\):
\[
V_{DCmin} = \sqrt{3} \left[ v_{Ldq}^2 + (\omega L I_{dq})^2 \right]
\]
(50)

In case of UPF (50) becomes:
\[
V_{DCmin} = \sqrt{3} \left[ E_m^2 + (\omega L I_{dq})^2 \right]
\]
(51)

Above equation shows relation between supply voltage (usually constant), output dc voltage, current (load) and inductance allowing to define the range of selection of the filter also. The inductor has to be designed with caution because the low inductance will increase the ripple in the current and will make the design more depending on the line impedance. At the contrary a high value of inductance \(L\) will reduce the current ripple, but at the same time reduce the operation range of the converter.

The voltage drop across the inductance has influence for the line current. This voltage drop is controlled by the input voltage of the PWM rectifier, equation (31), however, equation (28) limits its maximum value to the DC-link voltage. Consequently, a high current (higher load at the DC-link side) through the inductance requires either a high DC-link voltage or a low inductance (low impedance). Therefore, equation (51) can be used to define the maximal inductance value by:
\[
L_{max} = \frac{\sqrt{V_{DC}^2 - E_m^2}}{\omega I_{dq}}
\]
(52)

As explained previously the voltage-oriented control (VOC) will be implemented in this work. The voltage and current references are defined in equation (22) and equation (23) along with their transformation in the \(\alpha-\beta\) and \(d-q\) reference frames.
The power flow reference will be adopted from the mains or generator source towards the load, as well as the current as described in ‘figure 11’.

![Figure 11. Power Flow Reference.](image1)

The voltage-oriented control scheme is shown ‘figure 12’. It consists of:

1- PLL (Phase Locked Loop, used to calculate the voltage angle used for transformations \( \text{dq} \rightarrow \text{abc} \) and \( \text{abc} \rightarrow \text{dq} \) [30-33].

2- Voltage and current \( \text{abc} \rightarrow \text{dq} \) transformation blocks and voltage transformation block \( \text{dq} \rightarrow \text{abc} \) [22,29].

3- The controller that consist of 2 loops (outer and inner), it is worth mentioning that the inner loop contains a de-coupler that solves the cross coupling created by the \( j\omega LI_{\text{dq}} \) factor after transformation in \( \text{dq} \)-reference frame. [22,29].

4- Space vector pulse width modulation block that creates the bus signal functions \( S_{\text{abc}} \) responsible for triggering the transistor blocks according to equation (27) [28].

The block diagram is simulated in Matlab/Simulink and an assessment for the controller is provided with different test response to validate its feasibility as well as general outputs.

![Figure 12. Block diagram schematic.](image2)
The direct reference current is derived from the power relationship in equation (46) and equation (53), and set to be constant, as for the quadrature reference current is set to 0 to simulate a UPF behavior [22].

\[ P = \frac{V_{DC}^2}{R_{load}} \]  

\[ i_d = I_m = \frac{2V_{DC}^2}{3E_m R_{load}} \approx 224.536 \text{ A} \]  

Where \( P = 110 \text{ kW}, V_{DC} = 800 \text{ V}, E_m = \text{Grid amplitude} \).

The measured value of \( i_d \) is expected to be equal to the calculated value if the load is supplied by the generator only.

4. The process of combining system components:

To ensure uninterrupted power supply for the 110 kV load, it is necessary to install a battery system. The batteries are selected according to the catalogs of the Russian companies "Liotech" and "SSK". The batteries of these companies can operate at temperatures of -40 up to +50°C, have a high specific energy of around 85 Wh/kg. SSK batteries have a nominal capacity of 20 up to 80 Ah and a voltage range from 25 to 880 V [34] (Table 5). Liotech batteries on the other hand, have a capacity of 170 up to 770 Ah and a voltage of 3.2 V [35] (Table 6). The batteries of both companies have approximately the same capacity (Wh).

When choosing Liotech batteries, to create a module with a voltage of more than 500 V, a large number of batteries in series is required, which renders the installation work to become more complicated and may decrease the reliability of the system. Therefore, it is better to choose SSK batteries.

### Table 5. Technical data of main produced models of SSK batteries 550 V.

| Model | Nom. Capacity C3, (Ah) | W (mm) | L (mm) | H (mm) | Weight (Kg) | Specific Energy (Wh/kg) |
|-------|------------------------|--------|--------|--------|-------------|------------------------|
| SSK 20/C3-Ah-550 V 153-IMP-2 | 20 | 620 | 230 | 500 | 93.0 | 85 |
| SSK 30/C3-Ah-550 V 153-IMP-3 | 30 | 930 | 230 | 500 | 139.5 | 85 |
| SSK 40/C3-Ah-550 V 153-IMP-4 | 40 | 620 | 230 | 1000 | 186.0 | 85 |
| SSK 50/C3-Ah-550 V 153-IMP-5 | 50 | 700 | 230 | 1240 | 241.8 | 85 |
| SSK 60/C3-Ah-550 V 153-IMP-6 | 60 | 500 | 230 | 1860 | 279.0 | 85 |
| SSK 70/C3-Ah-550 V 153-IMP-7 | 70 | 1860 | 230 | 600 | 334.8 | 85 |
| SSK 80/C3-Ah-550 V 153-IMP-8 | 80 | 1240 | 230 | 1000 | 372.0 | 85 |

It is proposed to use a battery module having a voltage of 550 V, corresponding to the input voltage of the converter. The batteries are selected according to the load parameters presented in the table 7.

The battery system must provide power to the load for 10 minutes, provided that the maximum starting current of a motorized load is 7 times the rated current and its starting time is 3 s. 15% power
losses in the system are also taken into account. It is necessary to determine the type of the model and the number of batteries to be used depending on the capacity that each of the models under consideration can provide and based on the load parameters presented in table 7.

Table 6. Technical data of main produced models of Liotech batteries 3.2 V.

| Model (LT–LFP) | Nom. Capacity C3, (Ah) | W (mm) | L (mm) | H (mm) | Weight (Kg) | Specific Energy (Wh/kg) |
|---------------|------------------------|--------|--------|--------|-------------|-------------------------|
| 300P          | 300                    | 163    | 167    | 337    | 14.8        | 80.5                    |
| 380P          | 380                    | 163    | 167    | 337    | 14.8        | 82.2                    |
| 700P          | 700                    | 163    | 289    | 337    | 26.5        | 84.5                    |
| 770P          | 770                    | 163    | 289    | 337    | 26.5        | 93.0                    |
| 170           | 170                    | 85     | 150    | 346    | 6.9         | -                       |
| 240           | 240                    | 106    | 160    | 337    | 9.8         | -                       |
| 270           | 270                    | 106    | 160    | 337    | 9.8         | -                       |

Table 7. The battery’s model is selected according to the load parameters.

| Load Power P (kW) | Battery’s Voltage (V) | Nom. Current (A) | Inrush Current (A) |
|-------------------|-----------------------|------------------|--------------------|
| 110               | 550                   | 200              | 7 times            |

In the table 8, the calculation for each type of the 550 V SSK batteries is given, and the required number of needed batteries is determined. Each model has its own overall parameters and volume.

Table 8. The estimated dimensions of the batteries to determine their required number.

| 10 min Capacity (kA.sec) | Nom. Current (10 min) | Inrush Current (3 Sec.) | # of Batt. (+15% losses) | # of Batt | W (mm) | L (mm) | H (mm) | Vol. (m³) | № |
|--------------------------|-----------------------|-------------------------|--------------------------|-----------|--------|--------|--------|-----------|---|
| 72                       | 1.667                 | 0.019                   | 1.94                     | 2         | 620    | 460    | 500    | 0.14      | 1  |
| 108                      | 1.111                 | 0.013                   | 1.29                     | 2         | 930    | 460    | 500    | 0.21      | 2  |
| 144                      | 0.833                 | 0.010                   | 0.97                     | 1         | 620    | 230    | 1000   | 0.14      | 3  |
| 180                      | 0.667                 | 0.008                   | 0.78                     | 1         | 700    | 230    | 1240   | 0.20      | 4  |
| 216                      | 0.556                 | 0.006                   | 0.65                     | 1         | 500    | 230    | 1860   | 0.21      | 5  |
| 252                      | 0.476                 | 0.006                   | 0.55                     | 1         | 1860   | 230    | 600    | 0.26      | 6  |
| 288                      | 0.417                 | 0.005                   | 0.48                     | 1         | 1240   | 230    | 1000   | 0.29      | 7  |

There is no universal choice to be decided on, it all depends on the practicality of the solution: for example, if the battery will be installed in one electrical cabinet with the converter, it is better to choose a battery with a lower height. Then model No. 1 will be selected (tab. 3-4). However, if the height is not the main indicator, and the requirement for a practical solution is to minimize the width of the battery module, then the choice will fall on the second option.
On the other hand, if we take into account the aging and self-discharge factors, the third option may be the best option, since such a choice provides more energy than is necessary for a 10-minute standby time.

The use of supercapacitors to start the engine will be a good choice for many reasons, including the fast response of supercapacitors and the long service life they offer (1,000,000 cycles) compared to the battery service life (3,000 ... 6,000 cycles) [36,37].

If the engine start is not direct, but through the controller, then the time and amplitude of the starting current can be controlled. In this regard, the number of supercapacitors used will be minimized, and the necessary starting current will be provided to start the engine together with the battery, by the time the generator is ready to take the load. In table 9, the calculation of 125 V supercapacitors is given, which determines the required number of elements: “4”.

The proposed module of supercapacitors has its own overall parameters and volume.

Table 9. Technical data and design dimensions of Maxwell SC’s 125 V.

| Model | Number of SC | Nominal Voltage (V) | Nominal Capacity (W.h) | Nominal Capacity (kW.s) | W (mm) | L (mm) | H (mm) | Vol. (m$^3$) |
|-------|--------------|---------------------|------------------------|------------------------|--------|--------|--------|-------------|
| BCAP0063 P125 B08 4x | 1 | 125 | 140 | 504 | 619 | 33.3 | 365 | 0.01 |
| BCAP0063 P125 B08 | 4 | 500 | 560 | 2016 | 619 | 133.2 | 365 | 0.03 |

The SEPIC converter will be installed in an approximately 800x800x2000 enclosure with management and measurement modules.

Another similar cabinet will contain the AC-DC inverter with its control and measurement modules.

The DC-Link will be installed in a separate housing. All enclosures will be protected by convenient protective devices in accordance with the required norms and rules.

This set of equipment will be installed in a separate container with air conditioning system and mounted on a large trailer.

The power supply system for air conditioning and control is fed by a generator (or by the mains in case they are available). The estimated power demand for the Storage System equipment of the drive module is shown in table 10 [38].

Table 10. Power demand of the Energy Storage System equipment.

| Load Type            | Demand Factor | Installed Power (kW) | Consumed Power (kW) |
|----------------------|---------------|----------------------|---------------------|
| HVAC System          | 0.50          | 8.570                | 4.300               |
| Management System    | 1.00          | 0.085                | 0.085               |
| Lighting             | 0.15          | 0.470                | 0.060               |
| Fire Fighting System | 1.00          | 0.155                | 0.155               |
| **Results**          |               | **4,600**            |                     |

A smart switchboard is also mounted in the container and powered by the energy storage devices, as well as from a 150-kW diesel generator. The generator is installed in a 3250x1322x1893 soundproof enclosure [39] and is mounted on the truck. A cable system between the generator and the power cabinet will be selected and laid.
The power supply, control and management system form a mobile power station that will provide any mobile load within its power range.

Fuel storage for the diesel generator is carried out in a separate truck that accompanies the mobile power plant.

A primary schematic of the mobile station is shown in figure 13.

5. System implementation in Matlab/Simulink

The system of the rectifier and a resistive load of 110 kW installed in parallel to the DC-Link have been implemented in Matlab/Simulink together with an ESS consisting of Battery module and a supercapacitor module as shown in ‘figure 14’. The first simulation will test the system response when it is fed only by the generator. The aim of this test is to ensure a proper functioning of the rectifier and the generator as a power source supplying the load.

Since the batteries and supercapacitors were tested together with the SEPIC converter in previous section, the second simulation will verify the complete operation of the solution as mobile standalone power station. The following scenario will be processed and the results will be shown and discussed:

1. The simulation will start with the load and the ESS being disconnected. After the generator is ready, and the rectifier starts feeding the DC-Link, The ESS will join the operation at time 0.08 seconds.
2. Once the voltage is stable, the power supply system is now ready to take over the load at time 0.3 second.
3. At time 1.2 seconds, a fault simulation triggers the breaker of the generator, hence the ESS is holding alone all the load.
4. At time 3.2 seconds, the generator joins again the operation.
5. At time 3.7 seconds, the load gets disconnected. By this time the generator should be able to charge the ESS if needed.
6. The load is switched on at time 4.0 seconds while the ESS is being charged and the operations.
7. After that the ESS is switched off, at time 4.42 seconds and the generator now is supplying the load alone.
8. At time 5 seconds the ESS rejoin the power supply process.
9. At time 5.43 the load is switched off and the ESS.

It is worth to note that the time steps are selected after making sure that the operation in each specific time has reached steady state.

During this process the following variables were monitored and their results are displayed in the next section:

1. The DC-Link Voltage $V_{\text{DC}}$ to make sure it is maintained at 800 V.
2. The direct and quadrature currents of the grid to make sure that $\text{PF} = 1$. 

---

Figure 13. A primary schematic of the mobile station.
3. The phase angles of the voltage and the current of the grid to make sure that UPF is maintained and whether the system is operating in rectification mode or in regeneration mode.

4. The voltage and SOC% of the ESS modules.

5. The THD% of the grid voltage and the DC relative component of the DC-Link voltage.

![System implementation in Matlab/Simulink.](image)

**Figure 14.** System implementation in Matlab/Simulink.

6. **Discussion of results**

When the load is supplied only by the generator, the voltage controller binds $V_{DC}$ to its reference value (figure 15) with a response of around 300 ms with a minor oscillation setting a ripple in the DC-link voltage around:

$$\Delta V_{DC} = \frac{1 \times 100}{800} \approx 0.125\%$$  (55)

The quadrature current $i_q$ almost oscillates between -10 and 10 amperes.

The reference direct current $i_{d-reference}$ holds $i_d$ within its range.

The direct current $i_d$ oscillates around a mean value of 239 V with a variation of 14.4 V:

$$\Delta i_d = \frac{14.4 \times 100}{224} \approx 6.4\%$$  (56)

The voltage and current angles are superposed, which means their angle difference is zero.

The THD% of the generator voltage in ‘figure 16’ is 1.22% and the % of DC component THD is 0.02% which proves the clean operation of the rectifier.

When the complete system is working together, the value of $i_d$ will change and equation (54) will no longer be valid. However, the operation of the system in terms of maintaining the UPF is conserved as shown in the ‘figures 17,18 and 19’, as well as the value of the DC-Link voltage remains around 800 V with an error of 0.1%.
Figure 15. Grid/Generator side simulation results when load is supplied only by the generator.

Figure 16. THD% of the generator voltage.
Figure 17. G (ON) – ESS (ON) – Load (OFF): The ESS is turned on at 0.08 seconds and the voltage stabilizes around 0.16 seconds. $V_{DC} = 800.1V$, $i_q \approx 0$, $i_d > 0$, angle between $v_L$ and $i = 0$. This means that the UPF is achieved in rectification mode.
Figure 18. G (ON) – ESS (ON) – Load (ON): The Load is turned on at 0.3 seconds and the voltage stabilizes around 0.16 seconds. $V_{DC} = 800.1V$, $i_d \approx 0$, $i_d > 0$, angle between $v_L$ and $i = 0$. This means that the UPF is achieved in rectification mode.
Figure 19. G (OFF) – ESS (ON) – Load (ON): The generator is turned off at time 1.2 seconds and the voltage stabilizes immediately as per the SEPIC design characteristics. $V_{DC} = 799.5\text{ V}$, $i_q = 0$, $i_d = 0$, $v_L$ and $i = 0$. The rectifier is switched off.

Table 11. Performance of different operations.

| Status               | Time (sec) | Grid THD (%) | DC-Link (V) | THD DC (%) |
|----------------------|------------|--------------|-------------|------------|
| G(ON) ESS(ON) Load(OFF) | 0.2        | 1.19         | 801.0       | 0.04       |
| G (ON) ESS(ON) Load(ON)  | 1.0        | 1.19         | 800.1       | 0.03       |
| G (OFF) ESS(ON) Load(ON)  | 2.0        | No Voltage   | 799.5       | 0.01       |

Finally, the behavior of the ESS module is also monitored, which gives us the possibility to perform a convenient management on the batteries and supercapacitors according to the specifically applied cases. It can be noticed that when both the generator and the ESS modules are working, the rate of discharge of the ESS elements is less than when the ESS system is feeding the load alone.

According to the application, it can be decided if the storage elements will be charged from the generator, or from another source. However, the system shows its capability of charging and discharging the ESS as shown in ‘figure 20’ at the beginning of the operation and at time 3.7 seconds.
7. Conclusion
As a conclusion, the results of the simulation are satisfactory and the control reaches its objectives to achieve the UPF and maintain the DC-link voltage. The ESS is capable of providing online power support to the mains or the generator as well as to interfere in case of the occurrence of any fault. The complete system is feasible to be mounted on a single truck, hence the realization of a small mobile standalone electrical power station able to provide uninterruptable energy and able to service multiple types of loads in various conditions.

8. Future Consideration:
   1- Improve the controllers to reach better results, and apply different control techniques based on fuzzy control and artificial intelligence.
   2- Since the solution represents a form of distributed generation power sources, it is planned to modify the control system to interface with a command center.
   3- Realize a physical model of the converter.

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