Abstract— Nowadays the use of power converters, in particular, DC/DC converters in a large number of power electronics applications such as DC micro-grids (MGs) is an interesting subject in power systems. However, the use of such converters in MGs results in instability problems inflicted by the constant power loads (CPLs) because of their negative impedance feature. Thus, a controller with specific characteristics including, robustness and fast response to system dynamics to address unsteadiness issues and better performance of DC/DC converters feeding CPLs is vital. In this paper, a model prediction control (MPC) approach is introduced to tackle the de-stabilization problem and mitigate the destructive effect of CPLs, leading to a robust control approach as well as enlarging the system stability margin. To demonstrate and verify the usefulness of the proposed scheme in a real-time setup, the performance of the MPC controller applied to the DC/DC buck-boost converter feeding CPL is examined in a Model-In-the Loop (MiL) environment.

Keywords— DC/DC Buck-Boost Converters, Constant Power Load (CPL), Model Prediction Control (MPC), Model-In-the Loop (MiL)

I. INTRODUCTION

Recently, DC micro-grids (DC-MGs) have gained more popularity in comparison to AC ones, especially when they feed DC loads and incorporate renewable energy resources [1-4]. Despite DC-MGs advantages, DC-DC converters cause instability in DC-MGs in presence of CPLs, resulting in great fluctuations in the voltage and frequency cycles [5-7]. Hence, reducing the undesired effect of the CPLs is essential to stabilize and to increase reliability of DC-MGs [8]. It is indispensable to use nonlinear control due to the nonlinear characteristics of DC-MGs in presence of CPLs [9-11]. To overcome the de-stability problem and improve the efficiency of DC-MG with CPLs, in [10] a simple state feedback controller has been developed and the proposed nonlinear system in a Takagi-Sugeno (TS) fuzzy model is composed with a quadratic D-stability theory. To improve the stability of the DC-MGs imposed by CPL's undesired effect, in [9] a nonlinear disturbance observer and back-stepping method have been combined to develop a hybrid nonlinear controller. In [12] a model reference controller has been designed to mitigate the instability issue in DC/DC buck converter feeding a CPL. In [13], a robust semidefinite programming (SDP) technique has been deployed to obtain an equivalent-linear model from the nonlinear CPL dynamics so that to control the system by a robust linear controller.

The advent of the model predictive control (MPC) technique has made a significant revolution in various industrial control processes. Moreover, in the last decade, this control method has been effectively applied to operate a range of power electronics devices such as DC/DC converters [14-16]. MPC is an approach using finite prediction horizon and future nature of the system to apply control signals obtained by optimization of a defined cost function during control procedure in every state of the system. As a result, by enjoying the advantage of the robustness of this method, in every time step, the applied system variables inputs can be handled to achieve desired results. Other considerable beneficial features of MPC are simplicity in design, fast dynamics, and the ability to tailor the behavior to the specific problem encountered.

Time-varying CPLs have a great undesired impact on systems performance and the stability of such systems is further threatened, especially if the reference voltage changes simultaneously. To tackle the aforementioned problem, an MPC controller is formulated and developed for a DC/DC buck-boost converter non-ideal CPL. The performance of the proposed controller is verified under several operating circumstances for different typical micro-grid scenarios. Comprehensive Model-In-the Loop (MiL) examinations and comparative analysis are made to ascertain the performance of the MPC controller compared to the state-of-the-art techniques, in a real-time systematic scheme.

II. STATE-SPACE MODEL OF A TYPICAL DC/DC BUCK-BOOST CONVERTER WITH CPL

In Fig.1, the model of DC/DC buck-boost converter feeding a time-varying CPL is illustrated. The state-space model of the system under certain assumptions of operation in continuous mode is given by (1) and (2) [17].

\[ L \frac{di}{dt} = -(1-u)v + uE \]  \hspace{1cm} (1)

\[ C \frac{dv}{dt} = (1-u)i - \frac{P}{v} \]  \hspace{1cm} (2)

where \( i \in \mathbb{R} \) is the inductor current, \( v \in \mathbb{R} \) is the output voltage, \( P \in \mathbb{R} \) is the CPL's power, \( E \in \mathbb{R} \) is the input voltage and \( u \in [0,1] \) is the duty ratio of the switch control.
signal. The determined equilibrium set of the DC/DC buck-boost converter with CPL is given by (3) [17].

\[
E = \left\{(i, v) \in \mathbb{R}^2 \mid i - P \left(\frac{1}{L} + \frac{1}{F}\right) = 0\right\}
\] (3)

III. DESIGN OF PROPOSED MODEL PREDICTIVE CONTROLLER

The MPC technique uses a state-space model of plant and applies it to formulate the predictive control problem [14, 18, 19]. The primary stability related theoretical outcomes of MPC results from a state-space relation and can be used for both single-variable and multivariable processes. Also, it is capable to be developed to nonlinear processes. The general state-space of system dynamics is given by the following equations.

\[
x(k + 1) = Ax(k) + Bu(k)
\]
\[
y(k) = Cx(k)
\] (4)

Since the incremental control signal Δu(t) = u(t) - u(t - 1) in designing MPC, is more significant than u(t) signal itself, then by considering Δu(t), the state space can be written in a new common form. Therefore, with synthesizing this statement and the equations (4) the following presentation is gained [20]:

\[
\begin{bmatrix}
    x(k+1) \\
    u(k)
\end{bmatrix} =
\begin{bmatrix}
    A & B \\
    0 & 1
\end{bmatrix}
\begin{bmatrix}
    x(k) \\
    u(k-1)
\end{bmatrix} +
\begin{bmatrix}
    B \\
    1
\end{bmatrix} Δu(k)
\]
\[
y(k) = [C \ 0]
\begin{bmatrix}
    x(k) \\
    u(k-1)
\end{bmatrix}
\] (5)

The incremental state-space model takes the general following form with defining a new state vector as:

\[
\tilde{x}(k) = [x(k) \ u(k - 1)].
\]
\[
\tilde{x}(k+1) = M\tilde{x}(k) + N\Delta u(k)
\]
\[
y(k) = Q\tilde{x}(k)
\] (6)

By comparing (4) and (6) the relationship between (M, N, Q) and (A, B, C) can be easily obtained. To design the MPC controller for the nonlinear buck-boost converter feeding a CPL, the model described in (1) and (2) is turned into a discrete-time state-space form. For this purpose, the Euler method is provided that the switching period is less than the time constant of the circuit, the discrete-time model is obtained from the continuous-time mode as follows:

\[
x(k+1) = (1 - T_s A)x(k) + T_s B u(k)
\] (7)

Due to the intense nonlinear property of the system in the presence of the CPL to obtain A and B, it is necessary to linearize the system at each time step at the operation point of the system. According to the equations (1) and (2), \(\hat{A}\) and \(\hat{B}\) and \(\hat{C}\) are obtained as follows:

\[
\hat{A} = \begin{bmatrix}
    1 & 0 \\
    0 & 1
\end{bmatrix} + T_s \begin{bmatrix}
    0 & -1 + u_{old} \\
    -1 + u_{old} & L
\end{bmatrix} \frac{P}{C}
\]
\[
\hat{B} = T_s \begin{bmatrix}
    V_c + E \\
    L i_l / C
\end{bmatrix}
\]
\[
\hat{C} = \begin{bmatrix}
    0 & 1
\end{bmatrix}
\] (8)

where \(u_{old}\) is the previous control signal, \(V_c\) is the measured output voltage and \(i_l\) is measured inductor current.

Although various MPC algorithms may consider different cost functions to gain the optimum control signal, the common aim is to reduce the discrepancy of the future output \(y\) on the considered horizon, and the determined reference signal \(w\) as well as the control effort \(Δu\) should be penalized simultaneously. The general articulation for such a target function will be:

\[
J(k) = \sum_{p=N_1}^{N_2} ||w(k+p)[y(k+p)[k]]^2 + \lambda \sum_{p=0}^{N_u} |Δu(k+p)[k]|^2
\]

where N1 and N2 are the minimum and maximum prediction horizons, \(N_u\) is the control horizon, and \(λ\) is the weight coefficient that considers future behavior.

Output predictions over the horizon must be computed to optimize the cost function (9). By using an incremental model, predictions can be obtained by (5) recursively, resulting in:

\[
\hat{y}(k+j) = Q M^j \tilde{x}(k) + \sum_{j=0}^{j-1} Q M^{j-1} N \Delta u(k+j)
\] (10)

Unbiased estimation of the state vector \(x(k)\) is needed for the prediction. If the state vector would not be reachable then an observer should be included to compute the estimation by the following method:

\[
\hat{x}(k)[k] = \hat{x}(k)[k-1] + K \left(y_m(k) - y(k)[k-1]\right)
\] (11)

where \(y_m(k)\) is the measured output. Consequently, the predictions can be described along with the horizon employing:

\[
\begin{bmatrix}
    \hat{y}(k) \\
    \hat{y}(k+1) \\
    \vdots \\
    \hat{y}(k+N_u)
\end{bmatrix} =
\begin{bmatrix}
    Q M \tilde{x}(k) + Q N \Delta u(k) \\
    Q M^2 \tilde{x}(k) + \sum_{j=0}^{N_u} Q M^{j+1} N \Delta u(k+j) \\
    \vdots \\
    Q M^{N_u+2} \tilde{x}(k) + \sum_{j=0}^{N_u+1} Q M^{N_u+1} N \Delta u(k+j)
\end{bmatrix}
\] (12)

In vector form it can be expressed as:

\[
y = F \bar{x}(k) + Hu
\] (13)

where \(u^T = [\Delta u(k) \ \Delta u(k+1) \ \ldots \ \Delta u(k+N_u-1)]\) is the vector of future control increments, \(H\) is a lower triangular matrix such that \(H_n = Q M^{j+1} N\) and \(F\) is defined as:
The DC-DC buck-boost converter model explained in Fig. 1 is considered to verify the performance of the suggested MPC scheme in the presence of the CPL. Applying a non-ideal CPL in the buck-boost converter, the worst scenario situation which can be imposed on such power electronic systems is investigated from the stability point of view. The parameters corresponding to the circuit components of this setup are presented in Table I.

![Table I. Specifications of the DC-DC Buck-Boost Converter](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage, ( E )</td>
<td>48 ([V])</td>
<td>Capacitance, ( C )</td>
<td>6m(\text{F})</td>
<td>Reference output voltage, ( V_{ref} )</td>
<td>70 ([V])</td>
</tr>
</tbody>
</table>

The DC-DC buck-boost converter with the control mechanism is executed in the Model-In-the-Loop (MiL) simulation for real-time purposes. The MiL setup can emulate delays and errors which are not considered in the classical offline simulations. The overall schematic of the MiL setup based on dSPACE for the DC-DC buck-boost converter is depicted in Fig. 5. To ascertain the merits of the MPC scheme several real-time examinations are conducted and the obtained outcomes are compared with the sliding mode control (SMC) scheme [21].

![Fig. 2: Illustration of the real-time MiL test bed for the DC-DC buck-boost converter.](image)

**Scenario I:**

In the first stage, a generic time-varying CPL is applied to the DC-DC buck-boost converter, as illustrated in Fig. 3. The system outcomes (capacitor’s output voltage and CPL’s current) of the DC-DC buck-boost converter feeding time-varying are shown in Fig. 4.

From the outcomes of Fig. 4, it is revealed that the output voltage is precisely regulated by the MPC controller while the CPL’s current effectively tracks its references. Also, it is seen in Fig. 4 that despite the SMC controller can stabilize the system outcomes against the sever variations of CPL’s power, a small deviation has appeared in the transient and steady-state outcomes of the SMC controller. Thus, by adopting the MPC controller, an excellent performance stabilization of the DC-DC buck-boost converter can be achieved when the system is connected to non-ideal CPL and outperforms the other scheme.

![Fig. 3: Profile of the changes of constant power load.](image)

![Fig. 4: System responses of MPC and SMC according to the fix input voltage (Scenario I) a) capacitor’s output voltage b) CPL’s current.](image)

**Scenario II:**

In the second scenario, the input voltage of the battery system of DC-DC buck-boost converter varies to investigate the performance of the designed controllers under input voltage. To do this, four-level of input voltage (\( V_{in} = \{55 \text{[V]}, 66 \text{[V]}, 88 \text{[V]}, 120 \text{[V]}\} \)) are applied to the system and the real-time outcomes of the MPC and SMC controllers are demonstrated in Fig. 5 and Fig. 6, respectively. The curves of Fig. 5 reveal that in spite of the variations of input voltage and CPL’s power, the system outcomes of MPC controller remains stable. However, the outcomes of Fig. 6
with the application of SMC experience a relatively large overshoot and the converter requires more settling time to damp the deviations. Thus, a higher level of robustness can be attained by the MPC controller in comparison with the SMC scheme.

A time-varying non-ideal CPL was connected to the power electronic system to examine the applicability of the proposed MPC controller in the worst condition from an instability perspective. Real-time MIL examinations and controller synthesis are provided in various operating conditions and the real-time outcomes of suggested MPC scheme are compared with the SMC controller. The MPC controller was able to attain the desired outcome and outperforms the SMC controller to regulate the DC-DC buck-boost converter feeding non-ideal CPL under variation of input voltage, as it was confirmed in the MIL outcomes.

Fig. 5: System responses of MPC according to the input voltage variations
(a) capacitor’s output voltage
(b) CPL’s current.

Fig. 6: System responses of SMC according to the input voltage variations
(Scenario II)  a) capacitor’s output voltage
(b) CPL’s current.

V. CONCLUSION
In this study, an MPC controller is developed and applied to a buck-boost converter to suppress the voltage output deviations in typical scenarios of DC MG configurations.


