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A State-Space Approach to Modelling DC Distribution Systems

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Abstract—Many modelling methods for the analysis of dc distribution grids only consider monopolar configurations and do not allow for mutual couplings to be taken into account. The modelling method presented in this paper aims to deal with both of these issues. A state-space approach was chosen for its flexibility and computational speed. The derived approach can be applied to any dc distribution system regardless of its configuration and takes into account mutual couplings between phase conductors. Moreover, the state-space matrices can be derived in a programmatic manner. The derived model was verified empirically and by a reference model created in Simulink using PowerLib blocks. Subsequently, an illustrative system was analyzed, which showed the utility of the presented method in analyzing the dynamics of dc distribution systems. The presented method could especially be useful for the analysis, design and optimization of, for example, the stability and control systems of dc distribution systems.

Index Terms—dc distribution, distribution line, dynamic analysis, microgrid, modelling, state-space.

I. INTRODUCTION

FUTURE distribution grids face major challenges such as growing energy demand and the introduction of intermittent distributed energy sources [1]. Microgrids could provide the flexibility needed for these integration of large amounts of distributed energy sources [2]. However, for ac microgrids it is often necessary to decouple their frequency from other networks (by, for example, a solid state transformer described in [3]), which increases complexity and cost. Therefore, the adequacy of ac and/or dc for future system architectures could be reevaluated. Furthermore, technological advances and societal concerns also indicate that a reevaluation of the current distribution system is timely [4]–[7]. Broad adoption of dc distribution systems still faces several challenges, mainly due to the strong market inertia of ac systems, lack of standardization for dc devices and systems, and insufficient experience with its protection and control [8].

Previous research into dc distribution systems presents several methods to analyze these systems. Examples of modelling monopolar dc distribution grids according to their transfer functions can be found in [9]–[11]. Furthermore, different state-space approaches to the modelling of dc distribution grids are discussed in [12]–[15]. Additionally, a transient (EMTP) approach to the distribution system can be found in [16]. However, these models only consider monopolar configurations and, when extended to other configurations, do not allow for mutual couplings to be taken into account.

In this paper a non-transient state-space approach is chosen because of its computational speed, flexibility, and ease of use. The creation of a transient simulation environment optimized for dc applications is still imperative for the transient analysis of dc distribution systems. The modelling method presented in [15] allows for the programmatic derivation of the state-space matrices from a so-called incidence matrix. However, this method was designed for monopolar (single phase conductor) grids, and the derivation does not allow for mutual couplings or conductance to ground to be taken into account.

This paper is organized as follows: in Section II various modelling methods of (dc) distribution lines are reviewed. Section III presents the derivation of the developed state-space model. Section IV contains the validation of the developed model empirically and by using a simulation. Subsequently, Section V provides a dynamic analysis of an illustrative system. Lastly, in Section VI conclusions are drawn.
The validity of neglecting propagation delays depends on the other side, while in reality there are propagation delays. That changes at one side of the line are instantly discernible at they are frequency dependent. Moreover, it is usually assumed neglect of propagation delays and frequency dependent effects. The wavelength of the signal, which can be calculated by

\[ \lambda = \frac{c}{f\sqrt{\epsilon_r\mu_r}} \]  

where \( \lambda \) is the wavelength, \( f \) is the frequency of the signal, \( c \) is the speed of light, and \( \epsilon_r \) and \( \mu_r \) are the relative permittivity and relative permeability of the distribution line respectively.

Usually it is assumed that propagation delays can be neglected when the length of the distribution line is much smaller than the wavelength of the signal [18].

Since transients such as short-circuits often impose high frequencies on the system, models that include propagation delays are often called transient models. The most common transient models are based on distributed lumped element models or travelling wave models. Some specialized transient simulation environments that implement these methods exist such as PSCAD-EMTDC, EMTP, and ATP. In general transient models are more accurate than non-transients models, but are much more complex and require much more computational power and time for a simulation.

To circumvent the problem of wavelengths becoming comparable to the lengths of the distribution lines the model can be broken up into smaller pieces which individually have lengths much shorter than the wavelength of the signal. However, solving such a segmented model could quickly become time consuming depending on the required number of subsections [19].

Other models directly take the propagation delay into account in their equations. Popular examples of such models are the Bergeron model and variants on the travelling wave model [19], [20]. For the latter it is required to fit the frequency response of the model to a set of rational functions.

B. DC Distribution Line Modelling

Previous research on modelling dc distribution grids focuses mostly on monopolar (single phase conductor) dc distribution system architectures. However, since dc ground currents cause corrosion it is unlikely to only have a single distribution line in practice [21]. Moreover, bipolar grids are becoming more common, further increasing the likelihood of multiple phase conductors. The presence of multiple phase conductors introduces mutual couplings in the form of mutual inductance, conductance, and capacitance between the phase conductors. These couplings can have a significant effect on the dynamics of the system depending on the characteristics of the distribution lines. Furthermore, the conductance with respect to ground is usually not taken into account. While for overhead lines this can mostly be neglected, for underground cables the effect of conductance can be significant.

In this paper the distribution lines are modeled in a lumped element \( \pi \) configuration that includes mutual couplings. An example of this model for a bipolar (three phase conductors) distribution line is shown in Fig. 1.
The incidence matrix depicts the interconnections between the nodes in the network while the multi phase conductor incidence matrix extends this matrix by creating a node for each phase conductor at each node of the incidence matrix. The incidence matrix and the multi phase conductor incidence matrix are given by

$$ I_m(j, i) = \begin{cases} 1 & \text{if } I_j \text{ is flowing from node } i \\ -1 & \text{if } I_j \text{ is flowing in node } i \end{cases}, \quad (6) $$

$$ I'_m((j-1)m + k, (i-1)m + k) = I_m(j, i), \quad (7) $$

where the total number of nodes, distribution lines and phase conductors are depicted by $n$, $l$, and $m$ respectively. Moreover, one must cycle through all index combinations of nodes ($i$), distribution lines ($j$), and phase conductors ($k$) to create the complete incidence matrices.

With the inverses of the capacitance and inductance matrices the state-space equations can be derived to be

$$ \dot{U}_N = C^{-1}I_{DC} - C^{-1}I'^mT_{IL} - C^{-1}GU_N, \quad (8) $$

$$ \dot{I}_L = L^{-1}I'_mU_N - L^{-1}RI_L. \quad (9) $$

To solve these state-space equations they need to be molded into the form of

$$ \dot{x} = Ax + Bu, \quad (10) $$

$$ y = Cx + Du, \quad (11) $$

where $x$ is the set of state variables, $u$ is the set of input variables, $y$ are the output variables, and $A$, $B$, $C$ and $D$ are the state-space matrices. The state variables and input variables for different phase conductors are grouped by node or line, and are composed as

$$ x = [U_{1,1} \quad U_{1,2} \cdots U_{n,m} \quad I_{1,1} \cdots I_{n,m}], \quad (12) $$

$$ u = [I_{DC,1,1} \quad I_{DC,1,2} \cdots I_{DC,l,m}], \quad (13) $$

where $U_{i,k}$ is the voltage of the phase conductor $k$ at node $i$, and $I_{DC,j,k}$ is the current flowing in phase conductor $k$ of distribution line $j$.

The $A$, $B$, $C$, and $D$ matrices can now be derived from (8) and (9) and are given by

$$ A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \quad (14) $$

$$ A_{11} = -C^{-1}G, \quad (15) $$

$$ A_{12} = -C^{-1}I'^mT, \quad (16) $$

$$ A_{21} = L^{-1}I'_m, \quad (17) $$

$$ A_{22} = -L^{-1}R, \quad (18) $$

$$ B = \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix}, \quad (19) $$

$$ B_{11} = C^{-1}, \quad (20) $$

$$ B_{21} = \emptyset, \quad (21) $$

$$ C = I, \quad (22) $$

$$ D = \emptyset. \quad (23) $$

where $\emptyset$ indicates an empty matrix and $I$ indicates an identity matrix.
The impedance and admittance matrices $C$, $L$, $G$ and $R$ can be formed by employing (24) to (33). Firstly, the impedance and admittance matrices of all distribution lines, including (mutual) couplings between different phase conductors, are depicted as

$$R_{L,j} = \begin{bmatrix} R_1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & R_m \end{bmatrix},$$

$$L_{L,j} = \begin{bmatrix} L_{11} & M_{12} & \cdots & M_{1m} \\ M_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & M_{m(m-1)m} \\ M_{m1} & \cdots & M_{m(m-1)} & L_{mm} \end{bmatrix},$$

$$C_{L,j} = \begin{bmatrix} \sum_{k=1}^{m} C_{1k} & -C_{12} & \cdots & -C_{1m} \\ -C_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & -C_{m(m-1)m} \\ -C_{m1} & \cdots & -C_{m(m-1)} & \sum_{k=1}^{m} C_{mk} \end{bmatrix},$$

$$G_{L,j} = \begin{bmatrix} \sum_{k=1}^{m} G_{1k} & -G_{12} & \cdots & -G_{1m} \\ -G_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & -G_{m(m-1)m} \\ -G_{m1} & \cdots & -G_{m(m-1)} & \sum_{k=1}^{m} G_{mk} \end{bmatrix}$$

where the components of $R_{L,j}$, $L_{L,j}$, $C_{L,j}$ and $G_{L,j}$ indicate the resistance, (mutual) inductance, capacitance and conductance between the phase conductors of each distribution line.

Since a form of π-model is used the capacitance and conductance matrices of each node can be found by summing half of the capacitance and conductance of each distribution line connected to it:

$$C_{N,i} = \frac{1}{2} \sum_{j=1}^{i} C_{L,j} \ [I_{m}(j,i) \neq 0],$$

$$G_{N,i} = \frac{1}{2} \sum_{j=1}^{i} G_{L,j} \ [I_{m}(j,i) \neq 0].$$

If any external capacitance or conductance (such as grounding) is added to the network these could also be incorporated in these equations.

Finally, the impedance and admittance matrices that are used in the state-space equations can be formed:

$$R = \begin{bmatrix} R_{L,1} & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & R_{L,l} \end{bmatrix},$$

$$L = \begin{bmatrix} L_{L,1} & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & L_{L,l} \end{bmatrix},$$

$$C = \begin{bmatrix} C_{N,1} & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & C_{N,n} \end{bmatrix},$$

$$G = \begin{bmatrix} G_{N,1} & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & G_{N,n} \end{bmatrix}.$$
where \( i_L \) is the current flowing in the inductor, \( \Delta U \) is the voltage across the inductor and resistor, \( U_{dc} \) is the voltage of the (secondary side) capacitor, and the factor \( K \) conserves the power across the primary and secondary side of the converter (for example, \( K = U_e/U_{dc} \) for the ac/dc converter). Unfortunately, for a state-space approach the factor \( K \) needs to be linearized.

An inner control loop for the current, and an outer control loop for the voltage or power is employed. The equations for both (PI) controllers, in case the voltage is controlled, are

\[
\begin{align*}
\Delta U &= \left( \frac{K_{i,1}}{s} + K_{p,1} \right) (i_L^* - i_L), \\
\dot{i}_L &= \left( \frac{K_{i,2}}{s} + K_{p,2} \right) (U_{dc}^* - U_{dc}),
\end{align*}
\]

where \( K_{i,1} \) and \( K_{i,2} \) are the integral gains of the controllers, \( K_{p,1} \) and \( K_{p,2} \) are the proportional gains of the controllers, and \( i_L^* \) and \( U_{dc}^* \) are the reference values of the inductor current and capacitor voltage respectively.

To implement these controllers a state variable is required for the current controller (\( \alpha \)) and for the voltage controller (\( \beta \)). The chosen equations for these state variables are

\[
\begin{align*}
\dot{\alpha} &= K_{i,1} (i_L^* - i_L), \\
\dot{\beta} &= K_{i,2} (U_{dc}^* - U_{dc}).
\end{align*}
\]

By substituting (38) and (39) into (36) and (37) we arrive at the following equations:

\[
\begin{align*}
\Delta U &= \alpha - K_{p,1} i_L + K_{p,1} K_{p,2} (U_{dc}^* - U_{dc}) + K_{p,1} \beta, \\
i_L^* &= \beta - K_{p,2} U_{dc} + K_{p,2} U_{dc}^*.
\end{align*}
\]

Finally, the state-space equations can be derived by substituting (40) and (41) into (34) and (35). The state-space equations for the converter are then given by

\[
\begin{bmatrix}
i_L^* \\
U_{dc}^* \\
\dot{\alpha} \\
\dot{\beta}
\end{bmatrix} =
\begin{bmatrix}
i_L \\
U_{dc} \\
\alpha \\
\beta
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
i_L \\
U_{dc} \\
\alpha \\
\beta
\end{bmatrix} +
\begin{bmatrix}
K_{p,1} \\
K_{p,2}
\end{bmatrix}
\begin{bmatrix}
U_{dc}^* \\
\dot{U}_{dc}^*
\end{bmatrix},
\]

\[
A =
\begin{bmatrix}
-L & -K_{p,1} & \frac{1}{L} & K_{p,1} \\
0 & 0 & 0 & 0 \\
-K_{i,1} & -K_{i,1} & 0 & K_{i,1} \\
0 & -K_{i,2} & 0 & 0
\end{bmatrix},
\]

\[
B =
\begin{bmatrix}
\frac{K_{p,1} K_{p,2}}{L} \\
0 \\
K_{i,1} K_{p,2} \\
K_{i,2}
\end{bmatrix},
\]

\[
C =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix},
\]

\[
D = \emptyset.
\]

Fig. 5. Reference bipolar network used for the verification of the state-space model.

IV. Model Validation

The validity of the derived state-model is verified using a reference system shown in Fig. 5. In this network the ac/dc converter controls the voltage of the bipolar distribution network. The dc/dc converters represent a load and a source in the network. For the distribution lines three 1 km cables were used of which the mutual couplings were significantly increased to better verify the model for their effect on the system dynamics.

For the verification, an equivalent electrical network was built using PowerLib blocks in Simulink. To ensure an optimal comparison, both the developed state-space model and the PowerLib model were implemented in parallel in the same Simulink model. Consequently, identical time-steps are taken for both models. Moreover, to prevent the feedback loops of the converters from enhancing any discrepancies between the models, the converters and their control were modeled separately from the network and their output was provided to both models.

The verification scenario that is used can be found in Table I. In addition to a step in the voltage and power control signals, a short-circuit is induced at the node of the ac/dc controller at \( t = 15 \) ms. In Fig. 6 the output of the state-space model as a result of the verification scenario is shown.

<table>
<thead>
<tr>
<th>( t ) [ms]</th>
<th>( U_{dc}^* ) [V]</th>
<th>( P_1^* ) [W]</th>
<th>( P_2^* ) [W]</th>
<th>Short-circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>700</td>
<td>0</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>800</td>
<td>0</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>800</td>
<td>3200</td>
<td>-3200</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>800</td>
<td>3200</td>
<td>-3200</td>
<td>Yes</td>
</tr>
<tr>
<td>20</td>
<td>800</td>
<td>3200</td>
<td>-3200</td>
<td>Yes</td>
</tr>
</tbody>
</table>

From Fig. 6 several empirical verifications can be done. For example, it can be seen that the voltages of the nodes of the same pole conductor start to differ slightly as a result of a step in power. Furthermore, during the short-circuit the voltages of the neutral conductor drop quickly due to the capacitance between the poles and the neutral. Afterwards, the neutral voltages return to 0 V because of the conductance between the neutral and ground. Interestingly, the neutral current does not react much to a fast change in the pole currents (as a result of mutual inductance) due to the effect of the capacitance at both sides of the distribution line.
A more quantified verification can be done when comparing the results of the state-space model and the PowerLib model. The error between the two models did not go above $10^{-11}$ (Volt or Ampere) for any of the state variables during any moment of the verification scenario. As a summary the mean relative error for all 18 state variables is given in Fig. 7. From this graph it can be seen that the error between the two models is negligible. Please note that the spikes in the mean relative error are caused by variables that remain close to zero throughout the simulation.

This model has comparable accuracy for other dc distribution systems (regardless of power or configuration) as long as the lines are much shorter than the wavelength(s) of the signals and the frequency dependent components of the impedance and admittance can be neglected.

V. SIMULATION OF A BIPOLAR DISTRIBUTION GRID

In the previous section the validity of the state-space model was verified. In this section a more complex example of a bipolar dc distribution system is modelled and investigated.

The schematic of an illustrative distribution system is shown in Fig. 9. At the node in the middle ($N_1$) the voltage of the distribution system is controlled, while the converters at the other nodes control their own output/input power. The incidence matrix for this network can be derived from the figure and is given by

$$I_m = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}. \quad (48)$$

The scenario for which this distribution grid will be investigated is shown in Table II. First, the voltage will be stepped up, after which the various nodes will change their output/input power at varying times.

<table>
<thead>
<tr>
<th>$t$ [ms]</th>
<th>$U_{dc}^*$ [V]</th>
<th>$P_2^*$ [W]</th>
<th>$P_3^*$ [W]</th>
<th>$P_4^*$ [W]</th>
<th>$P_5^*$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>700</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>750</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>750</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>-1500</td>
</tr>
<tr>
<td>15</td>
<td>750</td>
<td>1500</td>
<td>-3000</td>
<td>0</td>
<td>-1500</td>
</tr>
<tr>
<td>20</td>
<td>750</td>
<td>1500</td>
<td>-3000</td>
<td>2250</td>
<td>-1500</td>
</tr>
<tr>
<td>25</td>
<td>750</td>
<td>1500</td>
<td>-3000</td>
<td>2250</td>
<td>-1500</td>
</tr>
</tbody>
</table>

The resulting voltages of the nodes and the currents in the distribution lines for the positive pole conductor are shown in Fig. 8. In the previous section it was shown that as long as no short-circuit occurs (and the system is balanced) little happens in the neutral voltages and currents. Furthermore, the negative pole quantities would, in this case, be identical but opposite in sign to the positive pole quantities.
From the voltage and current overshoot it can be seen that the inner and outer controllers of the converter are tightly tuned. Additionally, at the start of the simulation a slight transient can be observed that is caused by the conductance to ground of the distribution lines.

Since the network is connected in star with respect to the voltage regulator and is otherwise symmetrical, during the step up in voltage, the currents $I_{1+}$ to $I_{4+}$ are equal while the currents $I_{5+}$ to $I_{8+}$ are zero. Subsequently, during the symmetrical load step in $N_2$ and $N_5$ the voltages $V_{1+}$ and $V_{5+}$ get offset respectively, while the currents get distributed over all distribution lines other than $L_2$ and $L_3$. When at 15 ms a load is introduced in the system which is not directly compensated by an equal source, the average voltage in the distribution system drops, while the currents flowing from $N_1$ increase significantly. Finally, when the load is partly compensated by another source the average voltage rises again.

From this example it is clear the developed modelling technique is useful for the dynamic analysis of dc distribution systems. The validity of the presented model only depends on the wavelength(s) (see Section II) of the signals and therefore does not depend on the power rating of the system. The model is flexible enough to extend with more complex and more compelling scenarios, converter models, and control schemes (for example, droop control). Furthermore, the presented modeling method could be used to algebraically analyze the stability and control of dc distribution systems.

VI. CONCLUSION

This paper discussed the need for a novel and flexible modelling method for the dynamic analysis of dc distribution systems. Starting from previous research in modelling dc distribution systems and the comparison of different modelling methods used for ac lines, a choice for a non-transient state-space approach was made. The derived state-space approach can be applied to dc distribution systems with any number of phase conductors, nodes, and distribution lines, in any configuration. Furthermore, this model can be applied regardless of power rating and is also valid for transmission systems as long as the wavelength(s) of the signals are significantly smaller than the line lengths. Moreover, the state-space matrices of this model can be created programmatically, resulting in an easy to use method.

The model was verified using built in electrical components from PowerLib in Simulink. The PowerLib model showed strong congruency with the derived state-space model proving its validity. Moreover, the derived model behaved as expected during voltage, power, and short-circuit dynamics. Subsequently, a more complex distribution system was analyzed to showcase what the model can be used for.

In conclusion, this paper presents a flexible, accurate, and fast modeling method to analyze the dynamics of dc distribution systems. The state-space approach could in the future be used for the mathematical analysis, design, and optimization of, for example, control systems in dc distribution systems.