Abstract—In this paper, an accurate and simple dynamic model of a supercapacitor bank system for power system dynamics studies is presented. It is shown through comprehensive simulations in MATLAB-Simulink that an ideal capacitor representation is not always adequate. The proposed model is derived from a detailed RC circuit representation. Furthermore, a complete control system of the supercapacitor bank is also presented. The proposed model is easy to integrate in any power system simulation software and consists of maximally 4 easy-to-obtain parameters. The performance of the proposed model in grid frequency control and low-voltage ride through was tested in an IEEE 14-bus test system in DIgSILENT PowerFactory.

Index Terms—power system dynamics, power system simulation, power system modelling, power generation control

I. INTRODUCTION

The trend of increasing inverter-interfaced generation (IIG) in power systems throughout the world and subsequent reduction of synchronous inertia has motivated many research efforts to understand stability of low-inertia systems as well as developing new algorithms which enable the IIG participation in system frequency control and other ancillary services [1]–[5].

Supercapacitor energy storage system (ESS) [6] is an alternative to fast frequency response services provided by batteries and it can be used in coordination with batteries, e.g. supercapacitor can provide fast power injection or absorption to/from the grid immediately after an active power disturbance while batteries can take over in the longer time scale. The benefits of a supercapacitor system are as follows [7], [8]:

- supercapacitor can be charged and discharged at full power in the time scale of several tens of seconds or faster;
- supercapacitors are much smaller than batteries and can withstand significantly more charging/discharging cycles.

Relatively speaking, their high power / low energy density make them complementary with batteries which are low power / high energy density.

There are many papers utilizing supercapacitor technology in power system or industrial applications. However, as we will show in the following paragraphs, there were no detailed studies on the adequate complexity level of a supercapacitor model for power system dynamics studies, no rigorous derivation of the supercapacitor bank model and no complete representation of a supercapacitor bank system with associated control that can be easily integrated in power system simulation software. Furthermore, many papers use overly simplified supercapacitor models which do not adequately capture the supercapacitor dynamics. Hence we attempt to bridge this gap with this paper.

A. Literature survey

In [9]–[11], authors based their supercapacitor model on an ideal capacitor model with a constant capacitance. However, supercapacitor model is nonlinear and its capacitance varies with the applied voltage. Li et al. [12] showed real-time simulation of a wind turbine and a battery-supercapacitor hybrid system. They use a very accurate model of a supercapacitor from [13], but the detailed representation of the system and the controls are not shown. Arani and Saadany [14] use a supercapacitor cell as the DFIG DC link for virtual inertial response application, but they also based their supercapacitor model on an ordinary ideal capacitor. Rahim and Nowicki [15] use the supercapacitor system for DFIG fault-ride through, but their model is also based on ideal capacitor. Saw et al. [16] use a supercapacitor for electric vehicle applications, but the used model is numerical and not applicable to power system applications. Fang et al. [17] presented a hybrid ultracapacitor-battery system for implementation of a virtual synchronous generator and Garcia et al. [18] proposed a control strategy for a battery-ultracapacitor hybrid system. Both groups of authors based their supercapacitor model on an ideal capacitor as well. Molina and Mercado [19] presented a model of a DSTATCOM with ultracapacitor storage for power distribution system applications. Their model is very detailed, but it is represented in the RLC form which is not useful for implementation in power system simulation software. Furthermore, they did not show charging/discharging control. Many other papers [20]–[28] have the same shortcomings: too simple model and/or model not applicable for power system dynamic simulations application.

B. Contribution

As shown in the literature survey, all of the papers have the same shortcomings:

- supercapacitor is modelled as an ideal capacitor which is not always appropriate because the capacitance varies with the applied voltage and therefore the stored energy as well;
- supercapacitor energy storage system model is not applicable for power system dynamics because the model is either given in its RC/RLC form or the complete
control system was not shown which makes it difficult to integrate in power system simulation software;
- there were no studies which compared different levels of supercapacitor model accuracy.

To the best of our knowledge, there were no papers that developed an accurate, simple and complete model of a supercapacitor/ultracapacitor bank for power system stability studies. A complete model should include: accurate dynamics of a supercapacitor cell, supercapacitor DC current calculation, charge/discharge control, active power and voltage/reactive power inverter control as well as frequency control loop. Therefore, the contributions of this paper are as follows:
- detailed analysis and comparison of different supercapacitor models with varying levels of detail;
- derivation of the adequate level of detail of the supercapacitor model for power system dynamics applications (voltage and frequency control, transient stability studies);
- accurate dynamic model of the supercapacitor bank with all the necessary controls.

The presented model is easy to integrate in any power system simulation software. Rest of the paper is structured as follows: methodology is described in section II. Supercapacitor bank model is derived in section III. Complete supercapacitor bank system is presented in section IV. Performance of the model and simulation results are given in section V. Section VI concludes the paper.

II. METHODOLOGY

We will start by reviewing the relevant literature on supercapacitor modelling and showing the detailed state-of-the-art supercapacitor cell model. The model structure is identified from experimental measurements, most often impedance spectroscopy. Starting from the full model, we will start simplifying it by gradually reducing the number of parameters describing the model with the final goal of arriving to an accurate and as simple as possible model which captures the relevant supercapacitor/ultracapacitor dynamics. The model is intended to be used in power system short-term dynamics studies (transient stability, voltage control, inertial response and primary frequency control), i.e. the time scale of observation is up to 60 seconds after a disturbance. With every step of the way, we will compare different models with varying levels of detail to prove the validity of our simplification. Once the simplified model is derived, it will be scaled to form a supercapacitor bank of a higher rated power (MW order of magnitude). Then, the complete supercapacitor bank system with controls will be developed. The performance of the model will be shown in a standard IEEE 14-bus test system modelled in DIgSILENT PowerFactory 2019 software package. The type of simulations conducted are stability simulations (RMS, integration step 0.01 s), i.e. power electronic converters are represented by their average models.

III. SUPERCAPACITOR BANK MODEL DERIVATION

A. Super capacitor theory

Core of the super capacitor bank model is the supercapacitor cell. Overview of different supercapacitor models can be found in [29] while the state-of-the-art supercapacitor models can be found in [13, 29, 30]. Basically, these models are all similar and are based on impedance spectroscopy. All these models can be described with the same type of RC circuit consisting of three parallel sections as shown in Fig. I. The first branch (blue area) models fast dynamics, parallel branches (green area) model slower recombination phenomena after a fast charge or discharge and the last branch (orange area) models the long-term self-discharge phenomena [30]. We will gradually reduce the number of elements of this model in order to arrive to a model which is suitable for power system electromechanical dynamics time scale.

A few characteristics of a supercapacitor must be noted before we continue:
- majority of the ultracapacitor capacitance comes from \( C_{sc} \);
- series combination of parallel branches \( R_1^{sc}C_1^{sc} - R_n^{sc}C_n^{sc} \)
  is actually an infinite series of these parallel groups. However, 5 elements are enough to obtain an accurate model according to [30];
- capacitance \( C_{sc} \) as well as infinite sum elements \( R_k^{sc}, C_k^{sc} \)
  are dependent on the ultracapacitor voltage \( u_{sc}(t) \). This model is nonlinear with time-varying parameters. That is why ideal capacitor representation used in many papers is not always appropriate;
- the number of parallel branches in the green group is theoretically infinite, but between two branches and 4 branches are sufficient to achieve accurate results [30].

A few assumptions are made to simplify the model:
- \( R_s \) is the series resistance determined at very high frequency and is also voltage dependent [30]. However, since this resistance is small (< 10 mΩ) and the impact on the model performance is insignificant, we consider it as a constant parameter which is also usually done in reviewed literature on accurate supercapacitor modelling;
- temperature dependence of the parameters is neglected. Temperature is considered constant. The assumption is that the cooling of the system is adequate and that the system operates at room temperature. This effect can be included in a future version of the model, but we consider it not important for the initial derivation of the model for power system dynamics.

Parameters of the first branch are calculated according to [1]–[3] [30].

\[
C_{sc}(u_{sc}) = C_0 + k_u u_{sc}(t) \tag{1}
\]
\[
C_k^{sc} = \frac{1}{2} C_{sc}, \quad k \in \{1...n\} \tag{2}
\]
\[
R_k^{sc} = \frac{2\tau(u_{sc})}{k^2 \pi^2 C_{sc}} \tag{3}
\]

\( C_0 \) is the ultracapacitor capacitance at 0 V and \( k_u \) is a constant expressed in F/V. \( \tau(u_{sc}) \) is another experimentally determined parameter (it has a dimension of time) and can also be expressed as function changing linearly to the output.
Fig. 1. Detailed RC circuit of a supercapacitor cell

Voltage: \( \tau (u_{sc}) = \tau_0 + k_{sc} u_{sc}(t) \) \[30\]. However, it can also be approximated by \[30\] \[4\]:

\[
\tau (u_{sc}) \approx 3C_{dc}(R_{dc} - R_s),
\]

where \( R_{dc} \) is the equivalent series resistance experimentally obtained at very low frequencies (essentially DC). Naturally, \( R_{dc} > R_s \).

All the parameters of the first branch can be identified using manufacturer’s data sheet. Parameters of the parallel branches are more difficult to obtain since they must be obtained experimentally. Furthermore, these parameters are not universal and they depend on the time scale of the phenomena to be observed (described by the RC time constant \( \tau_{RC} = RC \)). The time scales are arbitrary, however they usually imply a range from several minutes to several weeks or even more \[29\], \[30\].

### B. Simplification of the supercapacitor cell model

In this section, we will show that the supercapacitor model for power system dynamics studies can be described with only the first branch and with none of the parallel groups \( R_k C_k \). Real experimental data from \[29\], \[30\] will be used in simulations for model simplification. This experimental data concerns two commercial supercapacitors which will be simulated with different models with varying levels of detail to show that our simplification is valid. Parameters of the parallel branches (green and orange section in Fig. 1) are determined experimentally through constant current charge test (Table I – Table IV).

Simulations of different model responses are conducted in MATLAB-Simulink using Simscape Electrical toolbox. The number of parallel branches is being sequentially reduced and the different model responses to the charge/discharge test are compared. Input to the model is the current \( i_{sc}(t) \) and output of the model is the supercapacitor voltage \( u_{sc}(t) \). Results are shown in Fig. 2. For clarification, 6 branch model represents the total number of branches (first branche, 4 parallel branches and a self-discharge branch). Results for both supercapacitors with different levels of detail (Fig. 26 and Fig. 2c) show that all the parallel branches as well as the self-discharge branch do not have an impact on the model accuracy for the time scale of interest. Therefore, all the branches except the first branch can be neglected.

In the next step, the adequate number of parallel RC groups in the first branch is determined. Results are shown in Fig 3. Here, the models are also compared to the ideal capacitor representation used in many papers to show the difference. Firstly, it can be seen that the parallel groups do not play a significant impact in the voltage response, although this depends on the model parameters since it can be seen that the effect is more pronounced for the Epcos model (Fig. 3b). Generally, accuracy is not lost if the parallel groups are neglected, although at least one should be included if greater accuracy is to be achieved.

Fig. 3d and Fig. 3e show that using the ideal capacitor representation will yield inaccurate voltage response. The value of the capacitance was chosen as \( C_0 \) of the respective supercapacitors model which is the worst case scenario. More accurate profile could be obtained by choosing a value which is much closer to the capacitance at rated voltage (Fig. 3e). Nevertheless, the ideal representation will not reflect the voltage transient effect which occurs when the charging or discharging current is discontinued. Fig. 3f shows the difference between stored energy for a detailed model and an ideal capacitor. If

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**TABLE I**

| Commercial supercapacitors parameters of the first branch from \[29\], \[30\] |
| --- | --- | --- | --- | --- |
| Cell | \( R_s \) [m\( \Omega \)] | \( R_{dc} \) [m\( \Omega \)] | \( C_0 \) [F] | \( k_v \) [F/V] |
| Maxwell BCA0150 | 6.3 | 7.1 | 108.4 | 10.8 |
| Epcos 110 F | 11.0 | 11.0* | 89.0 | 29.1 |

*Data not available, arbitrarily chosen

**TABLE II**

| Epcos 110 F 3 branch model parallel branches data \[29\] |
| --- | --- | --- |
| Parameter | \( R_1^p \) [\( \Omega \)] | \( C_1^p \) [F] | \( R_{leak} \) [k\( \Omega \)] |
| Value | 17.5 | 13.7 | 5 |

**TABLE III**

| Maxwell 150 4 branch model parallel branches data \[30\] |
| --- | --- | --- | --- | --- |
| Parameter | \( R_1^p \) [\( \Omega \)] | \( C_1^p \) [F] | \( R_2^p \) [k\( \Omega \)] | \( C_2^p \) [F] | \( R_{leak} \) [k\( \Omega \)] |
| Value | 80.2 | 28.0 | 3.73 | 27.1 | 66.6 |

**TABLE IV**

| Maxwell 150 6 branch model parallel branches data \[30\] |
| --- | --- | --- | --- |
| Parameter | \( R_1^p \) [\( \Omega \)] | \( C_1^p \) [F] | \( R_2^p \) [\( \Omega \)] | \( C_2^p \) [F] | \( R_3^p \) [\( \Omega \)] | \( C_3^p \) [F] | \( R_{leak} \) [k\( \Omega \)] |
| Value | 32.7 | 15.5 | 275 | 18.1 |
| Parameter | \( R_{leak} \) [k\( \Omega \)] |
| Value | 111 |
ideal capacitor representation has to be used, than it is better to use a capacitance value which is closer to the supercapacitor capacitance at rated voltage as the error is significantly smaller.

C. Building a supercapacitor bank model

In section III-B it was shown that the supercapacitor dynamics can be accurately represented using first branch only (gray section in Fig. 1) with at least one parallel RC group. To build a bank of a higher power rating, a certain number of cells \( n_s \) can be connected in series to form a string and a certain number of strings \( n_p \) can be connected in parallel to form a module. Modules can then be connected in parallel to form a bank. Assuming completely identical cells, it is easily shown using Kirchoff’s voltage and current laws that the voltage of the string \( u_{sc}^s \) and the current of the module \( i_{sc}^m \) are equal to (5) and (6), respectively.

\[ u_{sc}^s(t) = n_s u_{sc}(t) \quad (5) \]
\[ i_{sc}^m(t) = n_p i_{sc}(t) \quad (6) \]

Finally, the dynamic model of the bank can be built using circuit analysis in the time domain for the first branch only by setting \( u_{sc}(t) \) as an output \( y(t) \), \( i_{sc}(t) \) as an input \( u(t) \). Capacitor voltages are chosen as state variables. Complete nonlinear model of the supercapacitor bank in the analytic form is described by (7)–(12) where \( R_k^s \) and \( C_k^s \) are defined by (2) and (3), respectively.

\[ u_{sc}(t) = i_{sc}(t) R_k^s + u_{C_k}(t) + \sum_{k=1}^{n} u_{C_k}^s = y(t) \quad (7) \]
\[ i_{sc}(t) = u(t) \quad (8) \]
\[ u_{sc}^s(t) = n_s u_{sc}(t) = n_s y(t) \quad (9) \]
\[ i_{sc}^m(t) = n_p i_{sc}(t) = n_p u(t) \quad (10) \]
\[ \frac{du_{C_k}}{dt} = \frac{i_{sc}(t)}{C_k} \quad (11) \]
\[ \frac{du_{C_k}^s}{dt} = -\frac{u_{C_k}}{R_k^s C_k} + \frac{i_{sc}(t)}{R_k^s C_k} \quad (12) \]

Complete block diagram of the supercapacitor bank model described by (7)–(12) is shown in Fig. 4.

IV. COMPLETE CONTROL SYSTEM

The complete control system consists of inverter PQ control, charge/discharge control, DC current calculation and frequency control loop. The block diagram of the complete supercapacitor bank energy storage system is shown in Fig. 5. P and Q are active and reactive power injected or absorbed by the inverter to or from the grid, while asterisk (*) denotes a set-point value. \( V_{ac}^{grid} \) is the AC voltage of the bus the inverter is connected to. \( i_{dc} \) and \( i_q \) are the direct and
quadrature axis currents of the inverter. Inverter is controlled in the grid voltage reference frame. PLL estimates the grid voltage angle as well as the frequency for frequency control block. DC current calculation block calculates the supercapacitor current for charging or discharging. Individual blocks are further elaborated in the following subsections.

A. Charge control

Fig. 4 shows the structure of this block. State-of-Voltage (SoV) measurement is used to control the charging and discharging process. Charging is stopped if the supercapacitor bank is charged to nominal voltage, while discharging is stopped when the supercapacitor voltage falls below a user defined low voltage threshold. Charging/discharging is enabled again when the voltage reaches a user defined minimum voltage level for charging/discharging. The input to the block are the $d$ and $q$ axis currents $i_d^s$ and $i_q^s$ from the PQ control, while the final inverter current set-points $i_d^*$ and $i_q^*$ are determined by this block. Simple low-voltage ride through logic and current limitation is also implemented in this block which won’t be shown since this something that can be found in many literature.

B. DC current calculation

Input to the supercapacitor model is the current, but in power system applications we usually deal with controlling the power, not current. This block calculates the charging or discharging DC current based on the actual inverter power output. Block diagram of this subsystem is shown in Fig. 7. It should be noted that this module as well as the supercapacitor model work with SI units, while other subsystems work in p.u. $I_{ch}^{max}$ and $I_{dch}^{max}$ are the maximum single cell charging and discharging current in A (e.g. ±100 A).

C. PQ control

Fig. 8 shows the PQ control structure of the supercapacitor bank inverter. In this case, the inverter is modelled as a controlled current source and the $d$ and $q$ axis currents are obtained from the active and reactive power control error, respectively. Measurement/control lag is also included in this block diagram. The term $i_d^* - i_d^s$ is a compensation term for active power during low-voltage ride through when the active power should be low and reactive power high. Reactive power or terminal voltage control can be both chosen. However, if reactive power control is chosen it will be overridden by terminal voltage control during low-voltage ride through.

D. Grid frequency control

This block is shown in Fig. 9. The input to this block is the grid frequency signal estimated by the PLL and the output is the requested change in power. The type of implemented algorithm for frequency response can be arbitrary. However, based on the supercapacitor characteristics, in this paper we
decided for two control loops which look identical. The bottom loop is a standard virtual inertial response with a washout filter to make the output signal more smooth since the time derivative operation inherently amplifies noise. The upper loop is more akin to a standard droop control, but it also has a washout filter which means this contribution will diminish in steady-state, hence the name quasi-droop.

The reasoning for this choice is the following: the supercapacitor does not have a lot of stored energy—if the standard droop control is employed then the supercapacitor output power is initially proportional to the frequency deviation. However, once the supercapacitor is discharged, the output power will fall to zero which will cause a bigger secondary frequency drop. By setting a large washout filter time constant, the output power will slowly diminish while the conventional units pick up. Therefore, the difference between the inertia control and quasi-droop control is in the washout filter time constant ($\tau_{w}^{d} \gg \tau_{w}^{i}$).

**V. SIMULATION AND RESULTS**

The performance of the proposed model is implemented and tested on a standard IEEE 14-bus test system shown in Fig. 10 in DlgSILENT PowerFactory. Three scenarios are tested: underfrequency event, overfrequency event and low-voltage ride through event. Base case is without the supercapacitor bank contribution and a response with an ideal capacitor representation is also tested. Supercapacitor bank is connected to bus 06. Parameters of the supercapacitor bank system and the test grid are given in Appendix A and Appendix B, respectively.

**A. Underfrequency / Overfrequency event**

At $t = 1$ s, 13.5 MW load at bus 13 is connected to trigger an underfrequency event. Supercapacitor cell is initially charged to 1 V. Results are shown in Fig. [11].

It can be seen that the ideal capacitor representation (with constant capacitance equal to the supercapacitor capacitance at rated voltage) accurately describes the nonlinear model up to the first nadir (Fig. [11]). However, the ideal representation gives overly optimistic results regarding the stored energy which can be seen by the prolonged discharge time in Fig. [11b]. Fig. [11d] On the other hand, detailed model is much more accurate and gives an accurate behaviour regarding discharge power and available energy (notice the bigger nadir of the secondary frequency drop around 7 second mark in Fig. [11a]).

Similar behavior can be observed for an overfrequency event (when the same load is disconnected from the grid) in Fig. [12]. Initial supercapacitor cell voltage is set to 2.3 V. In this case, the supercapacitor bank is quickly charging to compensate for the temporary surplus of generation. In this scenario, the ideal representation describes the nonlinear model much more accurately. This is because the ideal representation with maximum capacitance much more accurately describes the nonlinear model near rated voltage as shown in Fig. [3c]. However, if the initial voltage was not near rated voltage or if the ideal capacitor capacitance was lower, then the difference between the two models would be greater.

**B. Low-voltage ride through**

Here, the performance of the low-voltage ride through algorithm is tested. Initial supercapacitor cell voltage is 2 V (i.e. string voltage is 200 V). Supercapacitor bank inverter is set to control unity power factor with the grid ($Q = 0$). At $t = 1$ s, 13.5 MW load at bus 13 is connected to trigger an underfrequency event and the supercapacitor bank starts discharging. At $t = 2.6$ s, a three-phase short circuit is applied to bus 6 which is cleared after 400 ms at $t = 3$ s. Results are shown in Fig. [13].

It can be seen in Fig. [13b] and Fig. [13c] that the current, thus output active power are reduced when the voltage dips at $t = 2.6$ s (Fig. [13a]), i.e. voltage control takes priority over active...
power control, supplying the grid with reactive power from $t = 2.6$ s to $t = 3$ s (Fig. 13). Once the fault is cleared, the reactive power quickly returns to the initial set-point ($Q = 0$). Now, the whole system is speeding up and the supercapacitor bank system acts as a brake reducing the change in frequency as shown in Fig. 13b. Therefore, this simulation has shown that the low-voltage ride through algorithm performs adequately.

VI. CONCLUSION

In this paper, an accurate and complete supercapacitor bank model has been presented for use in power system dynamics simulations. Starting from the most detailed RC model of a supercapacitor cell, the model has been gradually reduced until arriving to the most simple representation which adequately describes the supercapacitor dynamics, confirmed by simulation experiments. The proposed model is described with only 4 parameters which are easy to obtain from manufacturer’s data sheet: capacitance at zero voltage, voltage-dependent capacitance part, DC resistance and high-frequency resistance. Furthermore, the presented model was compared to an ideal capacitor representation to show that such representation is not always accurate. Then, a supercapacitor bank was built using supercapacitor cells to form strings and modules based on the assumption of identical cells.

A complete control system is presented including DC current calculation, charge and discharge control, PQ control, grid frequency control and low-voltage ride through. The performance of the presented model has been tested in an IEEE 14-bus test system to show that the model behaves correctly. The proposed model is easy to implement in any power system simulation software (e.g. PSS/E, PowerFactory, etc.) since it consists of basic elements only (e.g. integrators, gains, etc.). The model structure can be easily reduced to an ideal capacitor representation by neglecting certain parameters (i.e. setting them to 0). The main drawback of the proposed model is that it wasn’t validated against a real supercapacitor bank, which will be done in future research.
Appendix A

Supercapacitor bank system parameters

\( n_s = 100, \ n_p = 10, \) number of modules: 10, module/bank rated power: 1 MW / 10 MW, \( C_0 = 1800 \ \text{F}, \ k_v = 444 \ \text{F/V}, \ \) \( R_{dc} = 0.29 \ \text{m}\Omega, \ R_s = 0.2 \ \text{m}\Omega, \ \) \( i_{ch}^{max} / i_{dch}^{max} = \pm 500 \ \text{A}, \) \( U_{ch}^{max} = 2.7 \ \text{V}, \ U_{start}^{ch} = 2.5 \ \text{V}, \ U_{min}^{ch} = 0.5 \ \text{V}, \ U_{dch}^{start} = 1.5 \ \text{V}, \) \( \tau_s = 50 \ \text{ms}, \ K_1 = K_v = 100 \ \text{p.u}., \ \tau_{w}^{i} = 1 \ \text{s}, \ \tau_{w}^{d} = 30 \ \text{s}, \) \( K_p = K_p^{d} = 1 \ \text{p.u.}, \ K_i^{i} = K_i^{d} = 400 \ \text{p.u.} \)

Appendix B

IEEE 14-Bus test system data

G01: HYGOV turbine governor and IEEETIS excitation system.
G02: TGOVI turbine governor (\( T_2 = 2.4 \ \text{s}, \ T_3 = 8 \ \text{s} \)) and IEEETIS excitation system.
G03: GAST turbine governor and IEEETIS excitation system.
G06: GAST turbine governor and IEEETIS excitation system.

G08: GAST turbine governor and IEEETIS excitation system. All grid and element parameters have default values from DlgsILENT PowerFactory unless specified otherwise.

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References

[1] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, “Foundations and challenges of low-inertia systems (invited paper),” in 2018 Power Systems Computation Conference (PSCC), June 2018, pp. 1–25, doi: 10.23919/PSCC.2018.8450880
