# MODELLING OF STATIONARY AND DYNAMIC DEMAND BEHAVIOR CONSIDERING SECTORAL AND REGIONAL CHARACTERISTICS

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## *ABSTRACT*

*Modelling the aggregate behavior of electrical demand is a complex task as the composition is strongly dependent on time and field of application. This paper provides a methodical approach to describe the stationary and dynamic behavior of demand in typical German regions. Important factors of influence are considered, e.g. properties of individual load types and seasonal fluctuations in their usage. The resulting load model enables the dynamic simulation of changes in active and reactive power demand caused by variations in voltage and frequency. Representative regions are defined as 'intermediate', 'industry' and 'households' and the load model is parametrized for behavior during midday, evening and night time on a monthly basis.*

## INTRODUCTION

The transition towards distributed, renewable generation and the subsequent reduced role of large centralized power plants will potentially result in future power systems operating much closer to permitted stability limits. Consequently, the need for a more accurate simulation of distribution systems from the perspective of the transmission grid arises. This is particularly relevant in the case of demand modelling, whereby different types of load exhibit different steady state and dynamic behavior. In order to accurately model demand behavior, a number of factors must be considered. The presented paper examines the voltage and frequency behavior of aggregated loads in distribution systems for a range of German regions. Both stationary and dynamic load performance are represented in a single model, considering sectoral and regional characteristics (Fig. 1). The resulting set of parameters is basis for simulation of aggregated regions in electrical transmission grids [1] and further investigations in terms of an increasing share of novel technologies for several future scenarios presented in future publications.

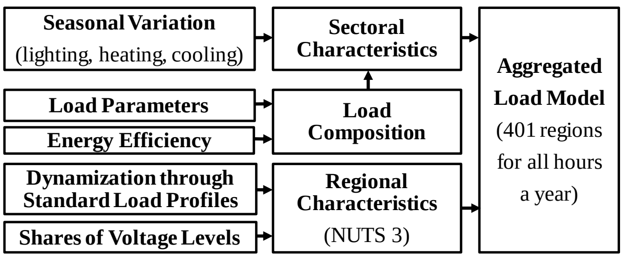


Figure 1: Illustration of the considered influencing factors of the aggregated load model

## METHODICAL APPROACH

To describe the aggregated behavior of electrical loads their change in active and reactive power consumption caused by a variation of voltage and frequency needs to be considered. For this, system operators around the world use different load models, which often focus on the stationary behavior and neglect the dynamic performance [2]. However, an appropriate modelling approach needs to combine both dependencies to achieve reliable results. To model the aggregated behavior information about the load composition is necessary. This means the share of individual loads on the total active and reactive power demand. Given that, the total load behavior composes out of the characteristics of the individual loads. The following paragraph presents the used load model and describes the basic approach of the aggregation method.

### Load Model Components

The applied load model consists of a stationary and a dynamic dependency on voltage and frequency (Fig. 2). A key advantage is the possibility to simulate dynamic events by using a simplified load model.

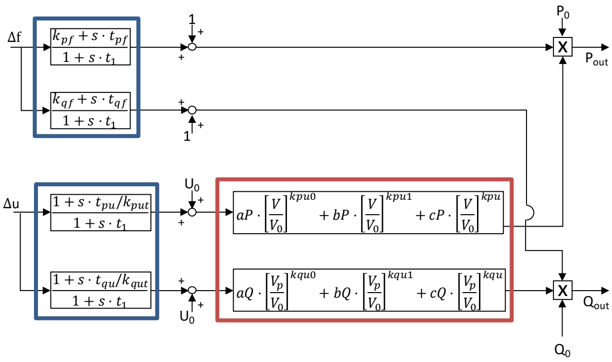


Figure 2: Block diagram of the relevant load model [3]

### Stationary Load Behavior

Stationary dependencies are understood as deviations of active and reactive power consumption referred to the nominal values after decay of all dynamic processes. For modelling the voltage dependency a polynomial approach is used, which is also known as "ZIP-model" (Fig. 2, red box). Its mathematical description is shown in equation (1) and (2). This approach separates a load composition into three basic types showing a completely resistive ($Z$, e.g. cooking plates), inductive ($I$, e.g. induction motors) or constant power characteristic ($P$, e.g. converters). This approach is known as "constrained approach" and gives information about the percentage shares of these basic types in the total load composition. Besides that, the polynomial approach can also be applied to derive ZIP values, which approximate the transfer function of an individual load mathematically. This is known as "non-constrained approach" and relevant for this publication. [2]

$$P = P_0 \cdot \left[ Z_\mathrm{p} \cdot \left(\frac{V}{V_\mathrm{N}}\right)^2 + I_\mathrm{p} \cdot \left(\frac{V}{V_\mathrm{N}}\right)^1 + P_\mathrm{p} \cdot \left(\frac{V}{V_\mathrm{N}}\right)^0 \right] \quad (1)$$

$$Q = Q_0 \cdot \left[ Z_\mathrm{q} \cdot \left(\frac{V}{V_\mathrm{N}}\right)^2 + I_\mathrm{q} \cdot \left(\frac{V}{V_\mathrm{N}}\right)^1 + P_\mathrm{q} \cdot \left(\frac{V}{V_\mathrm{N}}\right)^0 \right] \quad (2)$$

Furthermore, the frequency dependence is described by the factors $k_\mathrm{pf}$ and $k_\mathrm{qf}$ which represent the sensitivities of a change in active and reactive power consumption caused by a change of frequency (Fig. 2, blue box). A detailed description of these parameters is given in [4].

**Dynamic Load Behavior**

In reality, a change in power demand can only occur with finite speed (i.e. not instantaneously). The presented load model takes this into account by using a transfer function that shows a mixed proportional-integral-differential (Fig. 2, blue box). A derivation of this transfer function, given in [5], is based on the definition of elementary models which are suitable for the representation of typical grid components. The constants $t_1$, $t_{pu/qu}$ and $t_{pf/qf}$ describe the time intervals between the occurrence of a change in voltage and/or frequency and achieving 63 % of the stationary value of the apparent, active and reactive power.

## Component-based Approach

The presented load model is suitable to reproduce the behavior of a composition of different load types based on statistical information about their percentage shares on the total power demand. This approach is known as "Component-based Approach" and defined for a group of N loads by equations (3) and (4). These equations are used to aggregate load parameters for a known load composition by weighting the contributions of the individual loads to the total composition. In this context, the multiplier $c_i$ is representing this percentage share of a single load. The main idea behind the approach is that all loads contribute to the total load behavior dependent on their percentage share on the total demand.

$$(ZIP_\mathrm{p}, t_{1/\mathrm{pu/pf}}, k_\mathrm{pf}) = \sum_{i=1}^{N} \left[ c_\mathrm{i} \cdot (ZIP_\mathrm{p}, t_{1/\mathrm{pu/pf}}, k_\mathrm{pf}) \right] \quad (3)$$

$$(ZIP_\mathrm{q}, t_{\mathrm{qu/qf}}, k_\mathrm{qf}) = \sum_{i=1}^{N} \left[ Q_0 \cdot c_\mathrm{i} \cdot (ZIP_\mathrm{p}, t_{1/\mathrm{pu/pf}}, k_\mathrm{pf}) \right] \quad (4)$$

$$Q_0 = P_0 \cdot \tan(\arccos(\cos(\varphi_0))) \quad (5)$$

To aggregate the parameters describing the reactive power consumption, equation (4) contains an additional factor $Q_0$. It gives information about the amount of reactive power consumption depending on the active power demand $P_0$ and phase shift $\varphi_0$ as shown in equation (5).
Regarding the averaging of time constants, although this is an approximation, calculations show that the results are acceptable for the considered time constants.
The basic concept of the aggregation process is shown in Figure 3. First, the total power demand is split into its sectoral composition, then separated by different energy applications per sector and split into basic load types that represent the behavior of as many electrical loads as possible. A main advantage of this approach is that it is not dependent on in-field measurements and the possibility to examine future trends affecting the load composition (e.g. novel technologies). However, its outcome is dependent on quantity and quality of available statistical data. Thus, the approach is suitable for aggregate modelling of larger regions as statistical data cannot satisfy the claims of detailed modelling for individual units like industrial sites.

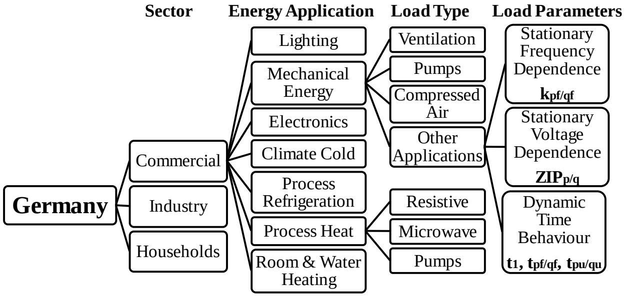


Figure 3: Basic principle of aggregated load modelling

# SECTORAL AND REGIONAL COMPOSITION PER ENERGY APPLICATION, VOLTAGE LEVEL AND TIME OF DAY

In order to apply the presented approach, information about the sectoral shares on the total demand in Germany and the composition of their end uses is necessary. In addition to that, information about the shares of demand categorized by region, the division of load between voltage levels and seasonal variations are considered.

## Sectoral and Regional Demand Composition

Initially, a large dataset describing the sectoral composition of the load demand in Germany is developed. This process builds up on statistical data presented in [6 – 8]. These publications share detailed information about the power demand in 55 typical commercial branches (e.g. retail, public and governmental, agricultural, science and research) and industrial facilities (e.g. automobile, paper, metal, chemical) as well as in households. To achieve a uniform structure, this information is gathered in 11 main categories using the "International Standard Industrial Classification of All Economical Activities" (ISIC) expanded by households as class V. Figure 4 shows the demand in Germany using an ISIC classification. Obviously, the industrial branches and households contribute the most to the total power demand.

As a result, the characteristics of loads in these sectors will dominate the aggregated load behavior.

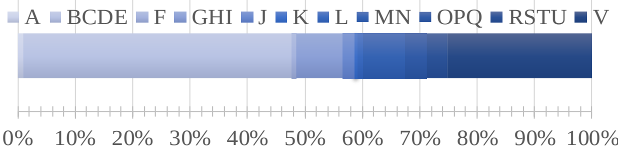


Figure 4: Shares of ISIC classes on the total load demand of Germany in 2015, $E_{el.,total}$ = 520 TWh [11]

The above-described classification is necessary to include a regional characterization describing 401 different regions in Germany which are defined in the "Nomenclature des Unites Territoriales Statistiques" (NUTS). On this occasion, the shares of employees per ISIC class on NUTS 3 level are suitable approximations of the percentage power demand in commercial and industrial branches. In the same manner, the percentage of the population on NUTS 3 level is used to approximate the power demand in households. Further information on this approach is presented in [9].

## Energy Application

In order to allow conclusions about the load composition per sector additional information regarding the end uses in different branches is required. Based on [6 – 8] end uses are split into seven groups. Those are lighting, mechanical energy, electronics, air conditioning, process refrigeration, process heat and room & water heating. Figure 5 shows the shares of energy applications in the annual demand in Germany separated by ISIC classes.

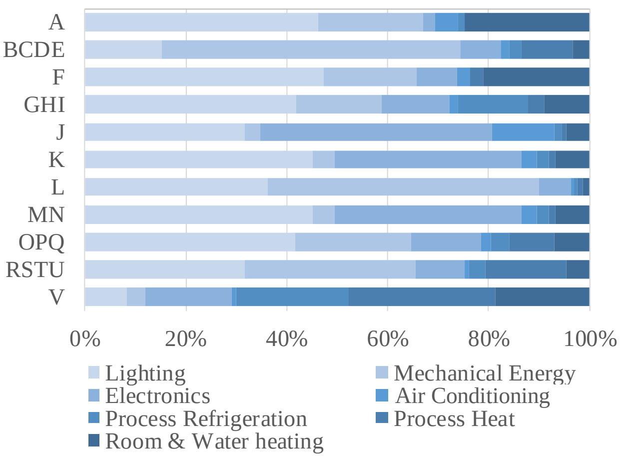


Figure 5: Shares of energy applications per ISIC classes

## Division of Load between Voltage Levels

The load is not distributed equally over voltage levels. These shares can be determined based on the distribution of different sized companies [9]. For this, the number of employees of average companies are used to approximate the division of load between voltage levels (Tab. 1).

Table 1: Shares of load demand separated by high (HV), medium (MV) and low (LV) voltage level [9]

| | Industry | Commercial | Households |
|---|---|---|---|
| **HV** | 57.10 % | 0 % | 0 % |
| **MV** | 36.40 % | 49.80 % | 0 % |
| **LV** | 6.50 % | 50.20 % | 100 % |

## Hourly Dynamisation

Standard load profiles are used to determine the percentage shares of sectoral demand per time of day [9]. These profiles describe the hourly demand of different branches on average days during a year (Fig. 6).

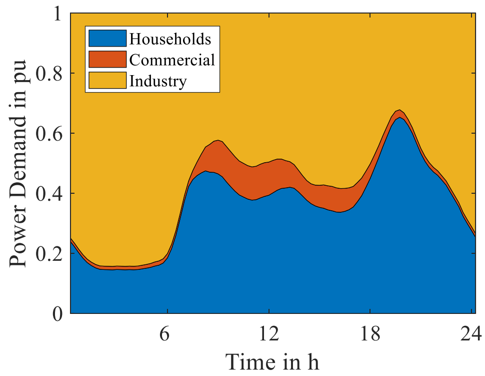


Figure 6: Hourly shares of sectoral demand on average day [9]

## SEASONAL VARIATION

Annual energy demand distributes unevenly throughout the year due to seasonal variations. These fluctuations are due to the changing demand for warm water and air conditioning. This leads to a higher percentage of resistive loads in winter (e.g. storage heating) and an increasing amount of inductive loads in summer (e.g. air conditioners). In addition, the lighting demand is higher during the winter compared to summer. To consider these dependencies associated energy applications need to be scaled monthly.

## Heating and Air Conditioning

An approximation of the monthly demand for heating and air conditioning can be made up by weighting heating and cooling degree days (HDD, CDD). Their derivation is based on hourly temperature measurements. In order to calculate them, several assumptions regarding the temperature an average person uses heating or air conditioning are considered. The researched database averages monthly HDD values of several locations in Germany from 2006 to 2015. [10]
In case of heating, a heating limit of 15 °C and a room temperature of 20 °C are assumed. For air conditioning a cooling limit of 20 °C is assumed.
The monthly HDD and CDD values are weighted annually to vary the power demand in the energy applications "air conditioning" and "room & water heating" by monthly scaling factors. In the case of heating, these factors need to be further modified dependent on the considered sector.

This is due to the assumption that room heating depends on seasonal variation, in contrast to water heating which is dependent on people's preferences (Tab. 2). Therefore, economic branches are split 50-50 between room and water heating, whereas industrial branches are considered 100-0 and households 36-64 [11].

### Lighting

The monthly lighting demand is mainly changing in households due to people's individual habits. In contrast to this, industrial facilities and economic branches are dependent on production processes and opening hours. Thus, scaling factors are only applied to households. The monthly scaling factors are based on sunrise and sundown times for the city of Kassel [10]. It is assumed that an average person gets up at 6 a.m. and go to bed at 10 p.m. in the evening. The time spans between waking up and sunrise as well as sundown and sleeping represent the daily lighting duration. Summed over a year, the monthly scaling factors are determined as shown in Table 2.

Table 2: Monthly shares of energy demand for heating, air conditioning (A/C) and lighting

| | Heating | | | A/C | Lighting |
|---|---|---|---|---|---|
| | **Commercial** | **Industry** | **Household** | | **Household** |
| **JAN** | 11,22 % | 12,26 % | 16,18 % | 0,00 % | 16.68 % |
| **FEB** | 10,61 % | 11,43 % | 14,53 % | 0,00 % | 11.78 % |
| **MAR** | 10,11 % | 10,75 % | 13,16 % | 0,03 % | 9.11 % |
| **APR** | 8,37 % | 8,38 % | 8,42 % | 2,03 % | 4.51 % |
| **MAY** | 7,21 % | 6,81 % | 5,30 % | 6,99 % | 1.93 % |
| **JUN** | 6,13 % | 5,34 % | 2,35 % | 18,56 % | 0.67 % |
| **JUL** | 5,52 % | 4,52 % | 0,71 % | 40,93 % | 0.98 % |
| **AUG** | 5,60 % | 4,63 % | 0,92 % | 25,02 % | 3.02 % |
| **SEP** | 6,64 % | 6,03 % | 3,73 % | 5,98 % | 7.05 % |
| **OCT** | 8,34 % | 8,34 % | 8,34 % | 0,45 % | 11.51 % |
| **NOV** | 9,51 % | 9,92 % | 11,52 % | 0,00 % | 15.02 % |
| **DEC** | 10,73 % | 11,59 % | 14,84 % | 0,00 % | 17.74 % |

## MODELLING OF ELECTRICAL LOADS

In the following subchapter, the aggregated load behavior is described by a few elementary load types, which are appropriate to model a large amount of different loads.

### Derivation of Basic Load Types

A theoretical derivation of basic load types was done in [12], whereby loads are classified and reduced to their physical functionality. This is justified by the similarity of many applications considering their physical background. In order to determine the shares of these basic load types on the energy applications (Fig. 3), it is assumed that they are similar in industrial sectors, commercial branches and households. The shares on the total demand per energy application are taken out of [13 – 16].

### Parameter Research of Basic Load Types

The research of suitable load parameters is a complex task as only a few publications deliver general values. The majority are based on measurements of arbitrarily selected electrical loads. Thus, for the basic load types, ZIP parameters are taken from [12] and [17]. In the same manner, the frequency sensitivities are taken from [4].
The most difficult task is considering the dynamic performance. Due to a high share of induction motors in the total load demand, the derivation of time constants is done in detail by using inertia constants of typical applications derived in the "Composite Load Model" [18]. Based on these applications suitable time constants can be calculated by theoretical relations in [4] and assuming an average slip of 2.5 %.
All other values are taken from [19] and [20]. Due to their focus on arbitrarily selected loads, corresponding time constants should be considered in future research.

## OUTCOME : LOAD PARAMETERS FOR MODELLING INTERMEDIATE REGIONS

The presented approach is used to determine sets of seasonal varying load parameters describing intermediate regions in Germany. Initially, parameter values of 401 NUTS 3 regions are calculated for 8760 hours a year using equations (3) and (4) dependent on the sectoral composition. Based on this, the resulting dataset is averaged monthly considering several time spans per day. These time spans are defined as day (1 p.m. – 3 p.m.), evening (6 p.m. – 9 p.m.) and night (1 a.m. – 4 a.m.).
Afterwards, regions are summarized in terms of their sectoral composition to minimize parameter deviations as industrial facilities and households differ in their sectoral compositions. Regions dominated by industry are defined as at least 60 % share on $ISIC_{BCDE}$ and such dominated by households with less than 60 % on $ISIC_{BCDE}$ and at least 40 % on $ISIC_{V}$. Using this, 75 regions dominated by industry and 13 by households can be identified. All others are classified as intermediate. The monthly course is shown in Figure 9 and presents the daily and seasonal variation by the example of aggregated coefficients $Z_p$, $I_p$ and $P_p$. It appears that seasonal and daily variation is higher than regional variation. Table 3 presents seasonal parameter values derived to model intermediate regions.

Table 3: Aggregated load parameters describing intermediate regions for different seasons by day, evening and night

| | Summer | | | Winter | | | Spring/Autumn | | |
|---|---|---|---|---|---|---|---|---|---|
| | ☀ | 🌅 | ☽ | ☀ | 🌅 | ☽ | ☀ | 🌅 | ☽ |
| $Z_p$ | 0.21 | 0.21 | 0.17 | 0.31 | 0.30 | 0.21 | 0.27 | 0.26 | 0.20 |
| $I_p$ | -0.11 | -0.17 | -0.21 | -0.06 | -0.14 | -0.24 | -0.10 | -0.17 | -0.25 |
| $P_p$ | 0.90 | 0.96 | 1.04 | 0.76 | 0.84 | 1.03 | 0.83 | 0.91 | 1.05 |
| $Z_q$ | 1.64 | 1.58 | 1.64 | 1.64 | 1.56 | 1.64 | 1.65 | 1.58 | 1.65 |
| $I_q$ | -1.77 | -1.65 | -1.90 | -1.67 | -1.51 | -1.87 | -1.74 | -1.60 | -1.91 |
| $P_q$ | 1.13 | 1.07 | 1.26 | 1.02 | 0.95 | 1.23 | 1.09 | 1.02 | 1.26 |
| $k_{pf}$ | 1.03 | 1.14 | 1.38 | 0.82 | 0.97 | 1.42 | 0.94 | 1.08 | 1.42 |
| $k_{qf}$ | 0.11 | 0.22 | 0.70 | 0.08 | 0.26 | 0.94 | 0.17 | 0.33 | 0.92 |
| $T_1$ | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 |
| $T_{pu}$ | 0.11 | 0.09 | 0.07 | 0.13 | 0.10 | 0.08 | 0.12 | 0.09 | 0.08 |
| $T_{qu}$ | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 | 0.04 | 0.05 | 0.04 | 0.04 |
| $T_{pf}$ | 0.55 | 0.67 | 0.81 | 0.38 | 0.55 | 0.82 | 0.47 | 0.63 | 0.83 |
| $T_{qf}$ | 0.11 | 0.22 | 0.70 | 0.08 | 0.26 | 0.94 | 0.17 | 0.33 | 0.92 |
| $Q_0$ | 0.43 | 0.46 | 0.46 | 0.41 | 0.45 | 0.45 | 0.41 | 0.45 | 0.45 |

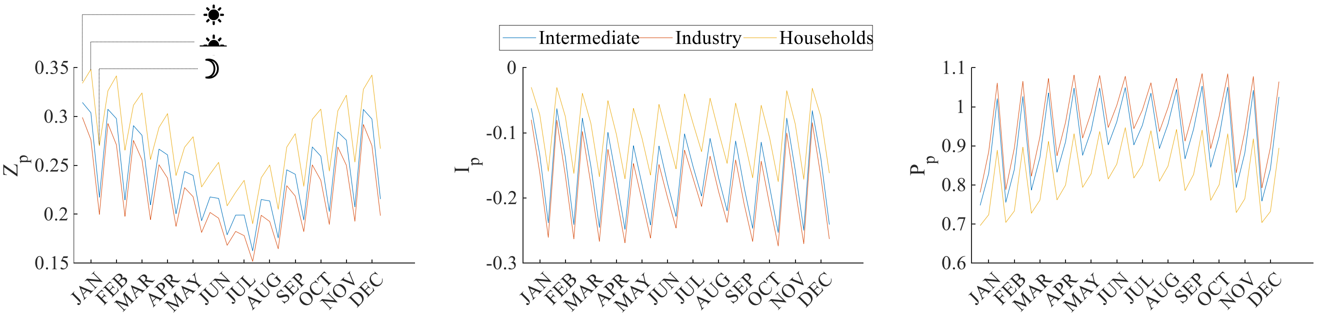

Figure 9: Average $ZIP_p$ values of intermediate, industrial and household areas split by day, evening and night per month

An increasing share of resistive loads in winter and by day leads to higher $Z_p$ values with a maximum in regions dominated by households. For motor applications ($-I_p$), the lowest values are reached at night and during transitional periods with minimum values in regions dominated by industry. Constant power loads ($P_p$) are most frequently used during summer and at night in industrial facilities. In general, intermediate areas spread between these others.

Figure 10 shows a comparison of the resulting step responses due to a change of voltage and frequency in intermediate regions. For this, several loads are parameterized based on the data presented in Table 3. The simulation results are compared to basic parameterization ($Z_{p/q} = 1$, black line), which is usually implemented in power system simulations. It appears that the dynamic performance differs strongly compared to the basic case. This applies also to the frequency dependence, which is commonly not considered in standard load models.

In the case of a voltage drop, the dynamic decay is hardly different throughout a year and day. It shows also that a change of voltage primarily affects the stationary deviation of reactive power. In contrast, the initial peak is higher in the case of the active power.

The observations referring to stationary deviation and initial peak are reversed in the case of a changing frequency. Moreover, the dynamic delay reaches its slowest change during winter and by day.

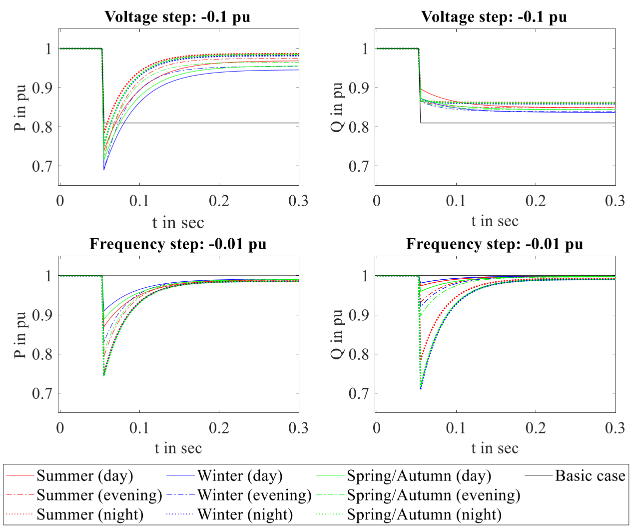

Figure 10: Change in active and reactive power due to a step in voltage and frequency compared to basic parameterization

In conclusion, a set of load parameters was derived which is suitable for aggregated modelling of intermediate regions in Germany by time of day and season out of the perspective of the transmission grid. The presented model extends the scope of commonly used load models by considering both stationary and dynamic behavior.

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